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IMPLEMENTATION AND EVALUATION OF AN INS SYSTEM FOR THE SHEPHERD ROTARY VEHICLE

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by

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The approach taken in this thesis was to implement two navigation sensors for a four-wheel drive and steer autonomous vehicle: An inertial measurement unit providing linear acceleration in three dimensions and angular velocity for the vehicle's global motion and shaft encoders providing local motion parameters. An inertial measurement unit is integrated with the Shepherd mobile robot and data acquisition and processing software is developed. Position estimation based on shaft encoder readings is implemented. The framework for future analysis including most general motion profiles have been laid.

The sensor's system performance was evaluated using three different linear motion profiles. Test results indicate that the shaft encoder provide a positioning accuracy better than 99% (typ. 7.5 mm for 1 m motion) under no slip conditions for pure translational motion. The IMU still requires further improvement to allow for both sensors to be combined to an integrated system.

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IMPLEMENTATION AND EVALUATION OF AN INS SYSTEM FOR THE SHEPHERD ROTARY VEHICLE

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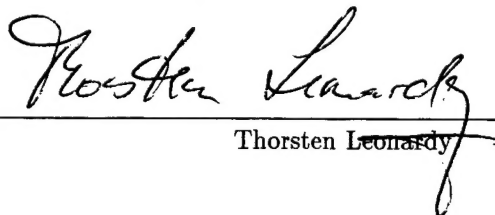requirements for the degree of

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I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

Landmines have become an ever increasing threat for the civilian communities in post-war scenarios. Several million land mines are scattered around the world annually causing more than 10,000 fatalities and more than 20,000 severe injuries to non-combattants.

Since effective multi-national proliferation treaties banning the use of anti-personnel mines are not yet in place and with major producers for those mines not likely to sign these treaties because of their important impact on conventional warfare, it is essential to develop and deploy equipment for detection of anti-personnel mines in mine-contaminated regions.

Moreover, many countries are downsizing their armed forces due to budget constraints and thus turning over formerly used defense sites to the local communities. Wide areas of these defense sites (such as proving ground, rifle ranges, ...) are contaminated with unexploded ordnance (UXO). The contaminated land must be cleared before transferring to civilian use.

B. OBJECTIVE

At present, there are not many effective means for mine and UXO detection available. The current approach to mine and UXO detection and clearance is labor and time intensive and dangerous: explosive ordnance disposal (EOD) personnel walks slowly over the area that is to be cleared, trying to detect buried, half buried or totally exposed material. Once an object is found, successive steps in the clearance process would include:

- detect,
- identify,
- excavate,
- defuse,
- transport

and

- dispose

the object in question. It is therefore desireable to develop a robust, low-cost tool for persuing the above steps through the use of robotics and advanced sensing techniques meeting the following requirements:

- Robustness for operation in rough terrain

- Expandability for different sensors and equipment

- Precise navigation tools

Multi-disciplinary research conducted in the Departments of Electrical and Computer Engineering, Computer Science, Aeronautics and Astronautics, and the Physics Department at the Naval Postgraduate School, centers around the development of a semi-autonomous robot system for land mine/UXO searching/processing tasks in humanitarian operations [2]. This project has required the cooperative effort of several NPS thesis. The emphasis of this thesis is the implementation of an integrated navigation system. In the long term, the system components will be comprised by a land vehicle, an aerial vehicle, and a ground-based control center.

The land vehicle, specifically designed for the aforementioned tasks is four-wheel steerable and drivable. A prototype vehicle called SHEPHERD is currently in use for this research project. The unique design of SHEPHERD provides a high level of sophistication for motion control for it to be able to precisely traverse rough terrain. The interested reader is referred to [1]. The scope of this project, in general, is very comprehensive and encompasses many scientific areas. In particular, interdisciplinary tools such as physics principles including coordinate transformations, kinematics and mechanics of rigid bodies, and electrical and software engineering tools are used, discussed and covered in this thesis.

In order to control the vehicle and implement efficient search patterns while at the same time reducing redundant search paths, precise knowledge of the vehicle's velocity and position is essential. Using an on-board inertial navigation system, the vehicle's acceleration can be measured and it's 3D motion precisely computed by the on-board computer. However, an inertial sensor alone can provide accurate position information only in the short term, but must be integrated with additional sensors if precise long term positional data is required. The vehicle's rough operation environment makes it essential that extremeley accurate position information is obtained. To meet this requirement, a Global Positioning System (GPS) receiver shall be integrated.

The purpose of this thesis is to implement and evaluate an integrated navigation system for SHEPHERD enabling the operation of the vehicle under extremely rough conditions while at the same time providing accurate position information. This thesis will examine the following research questions:

1. Provide the theoretical background for coordinate transformations,

2. Implement the hardware and software for an Inertial Measurement Unit (IMU),

3. Implement the software to determine position based on the on-board shaft encoders,

4. Develop a scheme for sensor fusion for slip-detection.

C.   ORGANIZATION

First, a brief overview of the computer architecture for the Shepherd Rotary Vehicle is given in Chapter II. Secondly, Chapter III defines the basic reference frames that are being used throughout this project. The secondary means of determining the vehicle motion is given by shaft encoders that are used for each of four wheels for both, steering and driving. The software implementation is described in Chapter IV. Chapter V describes the implementation of a low cost inertial measurement system (IMS) both in hardware and software. Its purpose will be to complement the shaft encoder system in situations were slip occurs. How both systems may be unified for slip detection and to further improve the performance of the navigation system is investigated in Chapter VI. Finally, the success and limitations of the use of the system described herein is summarized in Chapter VII providing essential results of this research and recommendations for future research in this area.

II.   SYSTEM OVERVIEW

In this chapter we will give a brief computer hardware description of the system configuration for the SHEPHERD Rotary Vehicle. This complements the description given by Mays/Reid [1] and is intended to provide the essential information necessary to understand the cross-references to computer components given in the following Chapters.

All mechanical information for the mobile platform is extensively discussed by Mays/Reid [1]. However, we shall note at this point that the Shepherd Rotary Vehicle is a four wheel drive and steer mobile robot. The four wheels are steerable without limitations and can be rotated and driven in either direction (more than 360 degree of rotation space). The four wheel drive and steer capability shall provide the robustness required for operation in rough terrain (e.g., sand dune scenarios, ...). A side view and front view photo taken from SHEPHERD with a digital camera are shown in Figure 2.1 and Figure 2.2, respectively.

In Figure 2.1 we can can see the four suspension boxes for the four wheels, the steel plate that comprises the main support frame for the robot, the inertial measurement sensor mounted upside down below the steel plate, and a joystick that is used to manually steer the robot in the top right-hand corner. In addition, in the rear view photo you can see the Laptop computer, to its left a switchbox for connecting the Laptop to either a CONSOLE or HOST serial port, and to its right the joystick. Another view, shown in Figure 2.3 shows the Laptop placed on the steel plate and behind it the servo control rack and the VMEBus chassis.

The complete hardware architecture is comprised of the TAURUS Single Board Computer [3], a VME-Bus based single board computer with a Motorola MC68040 as main processor and several other on-board processing components and the VME-Bus. At present, this stand alone computer system is expanded with a servo controller unit that interfaces to the four wheels and a 16-channel differential input A/D-Board. Four channels of the A/D-Board are utilized for the inertial measurement unit (IMU) which is discussed in Chapter V. In the future, the system may be expanded with several other sensors through the use of the VME-Bus. Figure 2.4 shows a block diagram of the system configuration for SHEPHERD.

A.   TAURUS BOARD

This section describes the TAURUS single-board computer system's main features. The hardware is based on a dual processor platform using Motorola's 68040 as the main processor and
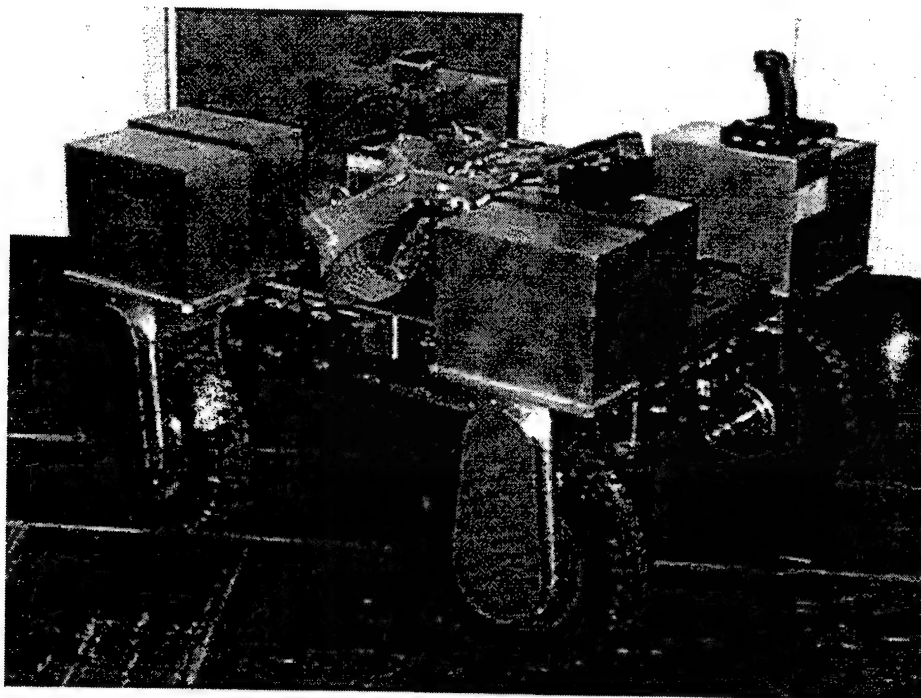
Figure 2.1: Side view from the SHEPHERD Rotary Vehicle.
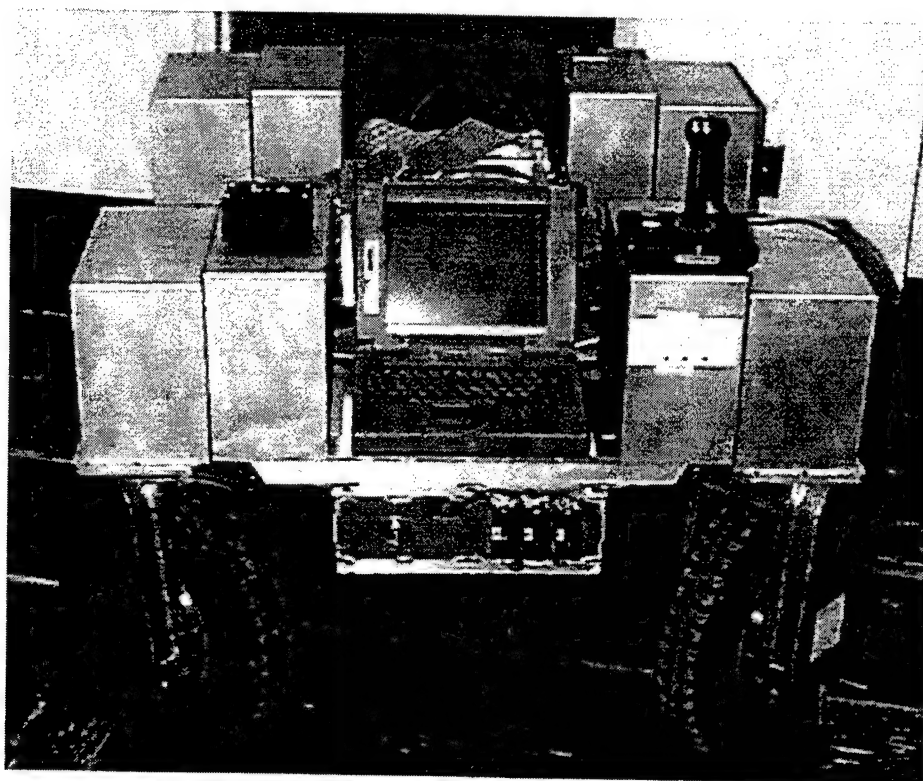
Figure 2.2: Front view from the SHEPHERD Rotary Vehicle with wheels rotated by 45°.

Figure 2.3: Top view from the SHEPHERD Rotary Vehicle. In the front, the Pentium Laptop used as a concole, in the middle the servo controller chassis, and in the back the VMEBus rack.
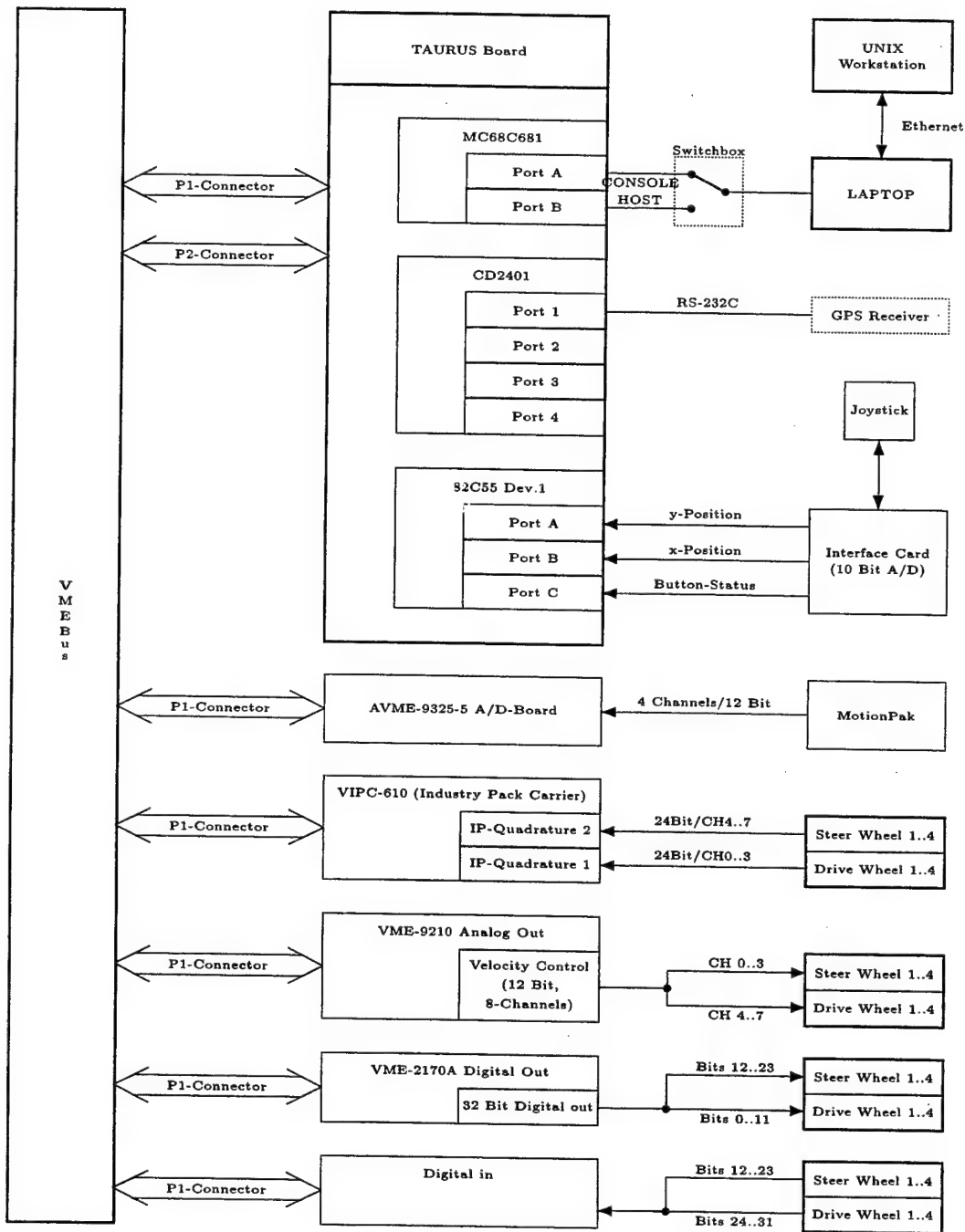
Figure 2.4: Shepherd Rotary Vehicle Hardware Configuration.

the 68030 as a slave processor for basic I/O functions. Signaling between both processors takes place via processor interrupts. The system is attached to a VME bus backplane providing the capability to expand the system as far as main memory and additional sensor devices are concerned. Among the many I/O functions that the TUARUS board provides are:

- six RS-232C serial communication ports (two through a DUART 68C681, and four through a CD2401 Communications Device)

- two 24 bit parallel ports

- several timer/counters: Five provided by the AM9513A System Timing Controller, one timer is provided in the 68C681 serial port device and eight timer/counters are available in the CD2401

- real time calendar clock device MK48T08

- SCSI Port

- Ethernet Port

More information can be obtained from [3] and the respective operating/user manuals for each device. Rather than focussing on all the technological aspects for each device, we merely focus on those important ones for understanding the operation of SHEPHERD.

1.   TAURUS Bug Monitor/Debugger

For start-up and debugging/monitoring purposes, a debugger/monitoring program called TAURUSBug resides in the memory region from `0xff800000` through `0xff9fffff` (memory bank 2, see [3], Chapter 2.2). The user may decide whether or not to use this program for the boot-up. However, in the sequel, the project group has made heavy use of the debugging tools provided by TAURUSBug.

2.   DUART 68C681

The TAURUS board features a 68C681 device which provides two dual asynchronous receiver/transmitter (DUART) serial ports with RS-232C interface. These two ports are utilized for up-/and downloading of executable code and data and for user interaction with SHEPHERD. Port A is called CONSOLE and Port B is called HOST. Both ports are connected through a switchbox to the laptop computer.

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3. Cirrus Logic Communications Controller CD2401

Up to date, only one of the four RS-232C serial ports provided by the Cirrus Logic Communications Controller CD2401 is used for interfacing the GPS receiver.

4. AM9513A Counter/Timer

The AM9513A LSI circuit provides a total of five independent 16-bit timer/counters which can be cascaded to a single 80-Bit timer/counter for long-term observations. The timer number five is used for deriving the motion control clock of T=10 ms: every 10 ms a timer interrupt is issued to trigger another motion control cycle. This 10 ms timer interrupt is clearly the heart of the system. Care should be taken that this interrupt is granted the highest priority level available. This leads to the decision to use timer five instead one of the other four.

5. Programmable Parallel I/O Port Device (Intel 82C55A)

The Taurus board is equipped with two Intel 82C55A devices each providing three 8-Bit wide ports (Port A, B, and C). Only the first device is currently in use for the motion control by means of a joystick. A simple PCB board interfaces an IBM-PC Joystick to this I/O device. However, some minor changes to the layout of the Joystick circuitry had to be made. Port A comprises the x-Position (an 8-bit digital value ranging from 0 ... 255 equivalent to joystick left to right), Port B gives the y-Position in the range 0 ... 255 equivalent to down (0x00) and up (0xff). Currently, only Bits zero and one are in use from Port C providing status information for the two switches on the throttle (pushing the left switch or the center switch on the trottle will set bit zero and pressing the right button on the throttle will set bit one). The other two push buttons on the left-hand side of the joystick have currently no function. In case that needed, they can easily be connected to any of the six remaining bits of Port C through the PCB board by use of pull-up resistors.

6. Interrupts

Both on-board and off-board Interrupts are supported by the TAURUS board. All on-board Interrupts are routed through the **Interrupt Steering Mechanism (ISM)** to either the 68030 I/O

Processor or via a VMEbus Interface Controller device (VIC068) to the 68040 Processor. Note that an interrupt can only be routed to one processor at a time. The VIC068 guides both, ISM interrupts and VMEbus interrupts to the 68040 processor. This is depicted by Figure 2.5. In accordance with [3], the local interrupts by on-board sources from the ISM to the VIC will be labelled as LIRQ-x whereas the interrupts form the VIC068 to the 68040 processor are labelled IRQ-x.
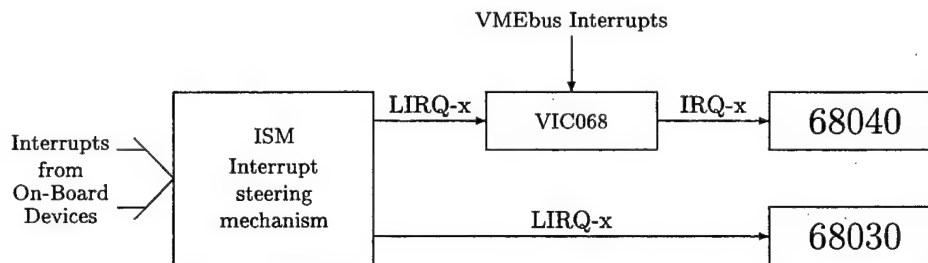
Figure 2.5: Servicing of on-board Interrupts or off-board VME-Bus Interrupts (From Ref. [3])

The ISM combines groups of on-board Interrupts to act as a single interrupt source towards either the 68030 or 68040 processor. It is important to note that the VIC068 device enables the programmer to shift the interrupt levels. In order to handle the proper handshaking in this case, the appropriate LIRQ-Shift-Register in the ISM would have to be set. The TAURUS user's manual [3] p. 2-71 gives the following example:

> ... if LIRQ-5 from the ISM is shifted in the VIC068 to IRQ-3, then the acknowledge signal from the 68040 processor to the VIC068 would be IACK-3 which would be passed on to the ISM device. LIRQ-SR5 (at $FFF4800A - upper nibble) would be set to shift [the] VIC068 IACK-3 input to output ISM-IACK-5.

Some facts that should be remembered:

- each Interrupt group is associated with an ISM Configuration Register Nibble.

- the MSB of each Nibble is the steering Bit, where '0' routes the interrupt to the 68030.

- the remaining three bits of each nibble encode the local interrupt level.

- upon Power-Up or RESET, all On-Board Interrupts are disabled.

- Taurus Vector Table Base address is at 0xffe10xxx where xxx = 4 × Vector Number.

B.   MOTION CONTROL

As indicated in the previous section, a motion control cycle is initiated with every 10 ms timer interrupt. In brief, this motion control cycle is given by the following sequence of logical blocks:

`readEncoder()`	Read all shaft encoders
`computeRates()`	Compute (angular) velocity for all steering and driving motors
`bodyMotion()`	Compute motion parameters for the vehicle's body (bodyMotion)
`wheelMotion()`	Compute the angles and speeds required for each wheel based on the results of bodyMotion
`driveMotors()`	Update the servos for driving and steering motors

The organization of the motion control cycle is described in more detail in Mays/Reid [1]. However, it should be noted that the source code as given there has been modified slightly to make the routines more efficient and thus less time consuming.

III.   REFERENCE FRAMES

This chapter gives a brief discussion on reference frames that are being used throughout this thesis.

A.   BODY MOTION

In the analysis of the motion of a rigid body, it turns out that considerable simplification in the mathematical formulas for rigid-body motion can be reached if the motion is described with respect to its **principal axes**. The principal axes are chosen such that the cross terms (sometimes called the products of inertia) of the moment of inertia tensor I vanish (see [4] for a more detailed analysis of this). The axes form a right-handed coordinate system with the origin usually taken to be at the body's center of mass (CM). However, at this point we are not concerned with the moment of inertia tensor.

1.   Body Reference Frame

For the purpose of describing the kinematics of a body moving on the Earth's surface the reference frame is chosen such that axes of the **body frame**, which we will call frame {B}, are given by the principal axes of the body given as follows:

x - longitudinal axis (oriented from rear to front of body)
y - transversal axis (oriented to the left)
z - normal axis (oriented pointing up, away from the center of the Earth)

2.   Sensor Reference Frame

Sensors will be employed with a vehicle in order to measure parameters pertaining to the vehicle's kinematics. The sensor will provide data relative to its own frame, which we will call sensor frame {S}. In general, this frame can be completely different from the body frame. If sensing data is provided in a Cartesian coordinate system, the only difference between {B} and {S} might be an offset (or translational difference) ${}^{B}P_{S,org}$.

3. Earth Reference Frame

In order to express the motion of a body as observed by an outside inertial observer we need to define a suitable inertial reference frame. An inertial reference frame is defined to be the frame for which Newton's laws of motion are valid. For a slow moving vehicle at a particular point on the Earth's surface, a suitable **reference frame** {R} is set up in the following way:

x - pointing north
y - pointing east
z - pointing down, towards the center of the Earth

We will see later in this chapter that the axes x,y and z of this coordinate system refer to the geodetic descriptions of latitude, longitude and geodetic height respectively. Since we do not anticipate any large scale motion (on the order of kilometers) it is sufficient not to concern ourselves with the irregular shape of the Earth and with the resulting mapping/projection problems.

B. GPS SYSTEM

In order to describe both the GPS Satellite motion and receiver motion, it is necessary to choose a common reference system. Most commonly, the motion is described in terms of velocity and position as measured in a Cartesian Coordinate System. The most applicable coordinate system for GPS systems are given as follows: Satellite and GPS receiver motion are described in terms of the Earth-Centered Inertial and Earth-Centered Earth-Fixed coordinate systems respectively. The systems in use are described in detail by Kaplan [5] and are briefly explained below:

1. Earth-Centered Inertial (ECI) Coordinate System

In this system, the origin is the center of mass of the Earth. Satellites orbiting the Earth obey Newton's second law of motion as described in this System. In the ECI system, the xy-plane coincides with the Earth's equatorial plane, the +x-axis points towards some fixed point in space (celestial sphere), the z-axis is taken to be normal to the xy-plane pointing towards the north pole. The set of axis forms a right-handed coordinate system. However, due to the Earth's inhomogeneous shape, irregularities in the Earth's motion cause the ECI frame not to be truly inertial. Therefore, the GPS system defines the ECI reference frame as given by the constellation at 1200 hr UTC on January 1, 2000.

2. Earth-Centered Earth-Fixed (ECEF) Coordinate System

For computing the receivers position, it is more convienient to use a system that is stationary in the earth frame. It is known as Earth-Centered Earth-Fixed (ECEF). As with the ECI frame, the xy-plane is coincident with the Earth's equatorial plane, the x-axis points in the direction of 0° longitude, the y-axis points in the direction of 90° longitude. The x- and y-axes therefore no longer describe fixed directions in inertial space. The z-axis completes the right-handed coordinate system.

3. Conversion between ECI and ECEF

Conversions between ECI and ECEF system are accomplished by means of matrix transformations (rotator matrices) which are not further described in this thesis. It is assumed that the Satellite ephemeris data is already translated into ECEF system.

4. World Geodetic System (WGS-84)

The Department of Defense invented a system to model all irregularities pertaining to describing the Earth's gravitational motion. This system is known as the World Geodetic System (WGS-84). In addition to modeling the gravitational irregularities, the World Geodetic System provides an ellipsoidal model of the Earth. The ECEF coordinate system is affixed to the World Geodetic System reference ellipsoid and thus, latitude, longitude and height of a receiver can be specified with respect to this ellipsoid.

C. TRANSFORMATIONS

To define and manipulate physical quantities such as acceleration, velocity and position we must define coordinate systems and find transformations for describing vectors given in one system with respect to the other. These transformations will be accompanied by conventions for their representation.

A great variety of similar transformations can be found in many textbooks. Not all of them are concisely formulated. It is thus rather confusing to relate different conventions given in different textbooks with each other; even though they may describe the same transformation. A

good introduction on spatial descriptions and transformations is given by [6] and we will therefore briefly outline the most important aspects and conventions as they pertain to our problem.

The inertial reference frame {R} is given by the set of coordinate axis {x,y,z} where the xy-plane is the plane parallel to the WGS-84 reference ellipsoid (that is, the earth's surface) with x pointing north, y pointing east and z pointing towards the geodetic center of the Earth. The frame {B} which is attached to the body is given by the set of axes { x', y', z' } with x' pointing forward, y' pointing to the left of the body and z' completing the right-handed coordinate system. Figure 3.1 shows both frames.
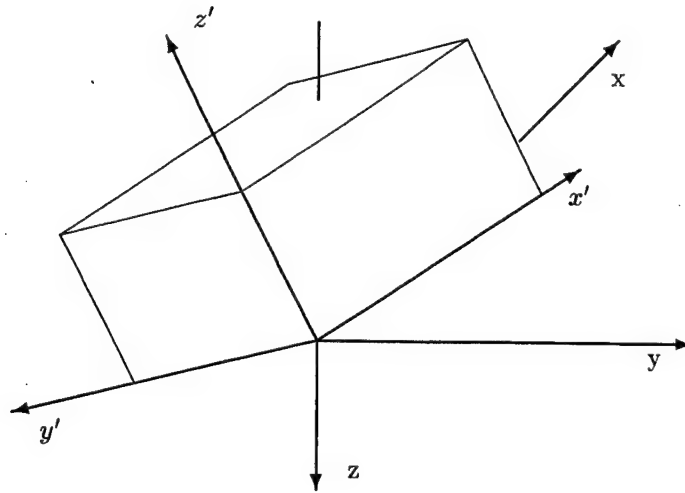
Figure 3.1: Coordinate Frame for Body relative to point on Earth surface. The x/y-plane spans the plane tangent to the Earth's surface.

There are two governing basic methods of representing the orientation of a body (with the Frame {B} attached to it) with respect to the reference frame {R}. One way is to express the principal directions of {B} (unit vectors x', y', z') in terms of the coordinate system {R} and stack these three unit vectors together as the columns of a 3×3 proper orthonormal **rotation matrix**

$$\mathbf{{}^{R}_{B}R} = [x'y'z']$$

where ${}^{R}_{B}\mathbf{R}$ has the properties that its columns are mutually orthogonal and have unit length and $det({}^{R}_{B}\mathbf{R}) = 1$. Moreover, it can be shown that the inverse of ${}^{R}_{B}\mathbf{R}$ is simply its transpose:

$$\mathbf{{}^{R}_{B}R^{-1}} = \mathbf{{}^{R}_{B}R^{T}} \tag{3.1}$$

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and thus giving rise to

$$\substack{R\\B}\mathbf{R}\,\substack{R\\B}\mathbf{R}^{-1} = \substack{R\\B}\mathbf{R}\,\substack{R\\B}\mathbf{R}^{T} = I \qquad .$$

Any vector $\vec{P}$ given with respect to $\{B\}$ can then be expressed in terms of $\{R\}$ by the transformation

$$^{R}\vec{P} = \substack{R\\B}\mathbf{R}^{B}\vec{P}$$

Since dealing with 3×3 matrices for describing orientations is usually very tedious, a second way of describing the orientation of a body can be derived from a result from linear algebra. **Cayley's formula** for orthonormal matrices (cited by Craig [6]) states that any 3×3 orthonormal matrix can be specified by just three parameters.

There are many ways to represent orientations with only three parameters. Not all of them are convenient and the reader may be easily confused while looking for those in different textbooks. In the discussion here we follow the conversion of Ref. [6].

1. Roll, Pitch, and Yaw

One way of describing the orientation of a frame $\{B\}$ relative to the reference frame $\{R\}$ is by describing the body's orientation by observing successive rotations about the three axes (x,y, and z) of the fixed refernece frame $\{R\}$. Craig [6] refers to this convention as **X-Y-Z fixed angles**:

1. start with the frame $\{B\}$ coincident with the reference frame $\{R\}$

2. rotate $\{B\}$ about $^{R}\vec{x}$ by the **roll** angle θ

3. rotate $\{B\}$ about $^{R}\vec{y}$ by the **pitch** angle ϕ

4. rotate $\{B\}$ about $^{R}\vec{z}$ by the **yaw** angle ψ

Each of the three rotations takes place about an axis in the fixed reference frame $\{R\}$. The resulting rotation matrix can be obtained by successively rotating the frame $\{B\}$ about single axes in the stationary frame $\{R\}$:

$$\substack{R\\B}\mathbf{R} = {}^{R}R_{Z}(\psi)\,{}^{R}R_{y}(\phi)\,{}^{R}R_{X}(\theta) \tag{3.2}$$

$$= \begin{bmatrix} cos(\psi)cos(\phi) & cos(\psi)sin(\phi)sin(\theta) - sin(\psi)cos(\theta) & cos(\psi)sin(\phi)cos(\theta) + sin(\psi)sin(\theta) \\ sin(\psi)cos(\phi) & sin(\psi)sin(\phi)sin(\theta) + cos(\psi)cos(\theta) & sin(\psi)sin(\phi)cos(\theta) - cos(\psi)sin(\theta) \\ -sin(\phi) & cos(\phi)sin(\theta) & cos(\phi)cos(\theta) \end{bmatrix}$$

where

$$^{R}R_{X}(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\theta) & -sin(\theta) \\ 0 & sin(\theta) & cos(\theta) \end{bmatrix} \tag{3.3}$$

$$^{R}R_{y}(\phi) = \begin{bmatrix} cos(\phi) & 0 & sin(\phi) \\ 0 & 1 & 0 \\ -sin(\phi) & 0 & cos(\phi) \end{bmatrix} \tag{3.4}$$

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$$^{\text{R}}\text{R}_{\text{Z}}(\psi) \quad = \quad \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad . \tag{3.5}$$

Therefore, a vector $^{\text{B}}\vec{a}$ given in frame {B} can be transformed with respect to frame {R} by the transformation

$$^{\text{R}}\vec{a} = {}^{\text{R}}_{\text{B}}\text{R}\,{}^{\text{B}}\vec{a} \qquad .$$

2. Euler Angles

Another possible description of the frame {B} with respect to frame {R} is given by the **Euler Angles**. As opposed to rotating the frame {B} in successive steps about the fixed axes of {R}, this description will involve successive rotations performed about the principal axes of the rotating frame {B} we are about to move:

1. start with the frame {B} coincident with the reference frame {R}
2. rotate {B} about $^{\text{B}}\vec{z}$ by the angle ψ
3. rotate {B} about $^{\text{B}}\vec{y}$ by the angle ϕ
4. rotate {B} about $^{\text{B}}\vec{x}$ by the angle θ

The resulting rotation matrix is the same as given above in Equation 3.2. Instead of naming the angles θ, ϕ, ψ as roll, pitch, and yaw respectively, they are now being referred to as the Euler Angles. Craig refers to them as the **Z-Y-X Euler Angles**. This transformation is equivalent to the one given by Fossen [7] on page 10 except that we exchanged the naming for roll and pitch ($\theta \leftrightarrow \phi$). The result obtained yields a fundamental statement as given by Craig [6]:

> ... three rotations taken about fixed axis yield the same final orientation as the same three rotations taken in opposite order about the axes of the moving frame.

In this work, we will make reference to the Eulerian angles and this mostly to the fact that the Eulerian angles are easier to recognize. However, the euler angles are equivalent to the roll, yaw and pitch angles.

In this chapter we have laid the framework for transforming vectors from one coordinate system to the other. We will apply this to the Inertial Measurement Unit and develop a scheme for determining the specific acceleration acting on a body even in the presence of the gravitational acceleration.

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IV. POSITION DETERMINATION WITH SHAFT ENCODER

This chapter describes the use of the shaft encoders for position determination. It complements and in some cases alters the results obtained by Mays/Reid [1]. As outlined in Mays/Reid [1], each servo motor is equipped with shaft encoders which record the actual angles for all eight motors. This should provide an easy means for direct position determination under the condition that no slip occurs. That is, the difference between an interval T=10 ms by which each encoder (driving and steering) advances is directly proportional to the distance travelled or to the angle each wheel was rotated and accordingly for the time of observation proportional to the linear and angular velocity.

It should be noted that the shaft encoders for the driving motors count positive for a clockwise rotation of the wheel. Thus, if all wheels are driving forward (which implies that wheels 1 and 3 are commanded with negative servo data) the shaft encoder readings will decrease for wheels 2 and 4. In the same manner, if all wheels are steering to the right (clockwise as viewed from above, with negative servo data commanded), the shaft encoder readings will increase for all wheels.

A. DETERMINING THE SERVO PARAMETERS

It might be necessary from time to time to verify and adjust the servo parameters in use for the motion control of SHEPHERD. Therefore, a few test routines have been implemented in the file 'motor.c'. These functions are

`driveTest()`	to determine the driving parameters
`steerTest()`	to determine the steering parameters
`stopTest()`	to determine the interaction between driving and steering for digits commanded to the servos being zero
`velocityTest()`	to obtain a relationship between digits commanded to the driving motors and actual angle rates observed
`circumferenceTest()`	to determine the circumference of the wheels

1. Steer Parameters

For determining the steering parameters the following method has been impemented in function 'steerTest()' in file 'motor.c':

1. align all wheels with hall sensor

2. clear the counters

3. save counter data in variable previous

4. rotate wheels for a certain number of turns and stop time it takes to rotate the wheel

5. read shaft encoder 'current' and compute the counter difference to obtain the rate of turn and number of counts for a turn

The source code is implemented as function 'steerTest()' in the file 'motor.c'. It should be noted that this test should only be conducted for free wheels off the ground, otherwise the vehicle may just wander around.

Some characteristic data corresponding to a specific velocity commanded is shown in Table 4.1. It can be seen from the Table that when steering the wheel, this would interfere with the drive counters as well. The work of Mays/Reid account for this fact by closed loop control. The data was taken for no load applied to the wheels (free turning wheels).

	Wheel 1	Wheel 2	Wheel 3	Wheel 4
count per turn	-92160.2	-92131.7	-92160.3	-92160.1
counts per degree	-256.00	-255.92	-256.00	-256.00
time per turn (sec)	6.97	6.98	6.98	6.98
drive count for turn	2048.0	2047.9	2048.0	2047.9

Table 4.1: Steering Wheel Data at Digits commanded 0x0b00 averaged over 10 turns.

Note when a positive value is commanded to all steering motors that the motion of the wheels as viewed from above is counterclockwise and the shaft encoder readings are negative! From the data, we can derive a relationship between the angular position of the steering motors and the encoder readings

steering wheel 1...4	1 degree = 256 counts
angle turned [radians]	$\theta = 6.8177 \cdot 10^{-5} rad/count$

Table 4.2: Conversion Factor for Steering all Wheels.

The results given above are in agreement with the findings from Mays/Reid [1]. With this data in mind, the angular velocity can be easily measured. All that needs to be done is to record the difference in steer encoder readings for an observation timeframe (T=10ms) and multiply by the above factor and divide by T.

2.   Drive Parameters

What is the goal to be determined in this section is: how does the driving data commanded to the drive servos (in the range from -1024 to +1023) relate to the actual driving speed. Moreover, how does driving interfere with the steering, is there any leakage at all? In order to determine this, two functions are in place for use within the SRK.

The function 'driveTest()' was written in order to determine how the drive encoder readings relate to the angular position of the wheel (if the wheel is viewed as a clock). All this function does is to record the difference in shaft encoder readings for a given number of turns completed. This observation gives rise to the number of counts per degree for driving the wheel. The function does not operate autonomous but rather requires user interaction. The user determines when to start and end the observation period. This procedure was conducted several times at different speeds - although the speed is not of our concern at this point. The results are given in Table 4.3.

driving at speed 0x0800 (1 turn)				
	Wheel 1	Wheel 2	Wheel 3	Wheel 4
count per turn	-102746	-103949	-105340	-104038
counts per degree	-285.41	-288.75	-292.61	-288.99
time per turn (sec)	10.85	10.63	10.97	10.87
drive count for 1 turn	n/a			
driving at speed 0x0800 (averaged over 3 turns)				
	Wheel 1	Wheel 2	Wheel 3	Wheel 4
count per turn	-103989	-104303	-103967	-104229
counts per degree	-288.86	-289.73	-288.80	-298.53
time per turn (sec)	10.85	10.63	10.97	10.87
drive count for 1 turn	n/a			
driving at speed 0x2000 (averaged over 10 turns)				
	Wheel 1	Wheel 2	Wheel 3	Wheel 4
count per turn	-103756	-104143	-104812	-104705
counts per degree	-288.21	-289.29	-291.15	-290.85
time per turn (sec)	2.704	2.698	2.729	2.727
drive count for 1 turn	n/a			
driving at speed 0x2000 (averaged over 100 turns)				
	Wheel 1	Wheel 2	Wheel 3	Wheel 4
count per turn	-104377	-102594	-104440	-104435
counts per degree	-289.92	-284.98	-290.11	-290.10
time per turn (sec)	2.72	2.71	2.72	2.72
drive count for 1 turn	63394.94	63297.88	63331.94	63337.61

Table 4.3: Data obtained for determining drive parameters with program 'driveTest()'.

It can be seen from the Table that the number of counts per degree for all wheels is given by approximately 290 counts/degree except for wheel two at the commanded speed of 0x0800.

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However, it is assumed that the user simply failed in observing the correct number of turns for this wheel. Another test run eventually with even more turns should be conducted. However, for ease of computation and in agreement to Mays/Reid [1], it is expected that for a given number of encoder counts, all wheels will advance by exact the same angle if commanded by the same digit and the conversion is given by

driving wheel 1...4	1 degree = 290 counts
angle driven [radians]	$\theta = 6.018376731 \cdot 10^{-5} rad/count$

Table 4.4: Conversion Factor for Driving all Wheels.

In a second step, a function 'velocityTest()' was implemented in the source file 'motor.c' in order to determine the driving speed as a function of servo data sent to the driving servos. The inner workings of this function are quite simple:

1. Align all wheels, set speed = 500.

2. Set all motors to speed.

3. Wait one second to let servos attain steady state.

4. Observe the difference in shaft encoder readings for an observation period of one second. Store the readings in main memory (starting at 0x00100000) at consecutive locations.

5. Decrease speed = speed -10.

6. If speed < -500 stop, otherwise repeat the loop with step 2.

7. Stop the test program.

Once the program was done, the data (steering and driving delta for every second) was downloaded as an ASCII dump to the notebook, converted to decimals and further analyzed using the MATLAB function 'velocity.m'. Although it was - based on the results from Mays/Reid - expected to obtain a nonlinear relationship between the velocity (which is proportinal to the difference in encoder readings) and the commanded digits, the results proved to be quite different.

For free floating wheels, the drive encoder advances for a given speed during the time interval of 1 sec are shown in Figure 4.1 and the equivalent steer encoder differences are shown in Figure 4.2. To solidify the results, a second experiment, now with the vehicle on the ground has been conducted. The results according to this experiment are shown in Figure 4.3 and Figure 4.4.

As can be seen from the graphs, both experiments show the same linear relationship for the driving of all wheels with just slightly changing parameters and in addition to this, the interaction from driving to steering for each wheel is insignificant and can be neglected. The test was conducted a total of three times, two times with the wheels on the ground and the vehicle moving in a straight
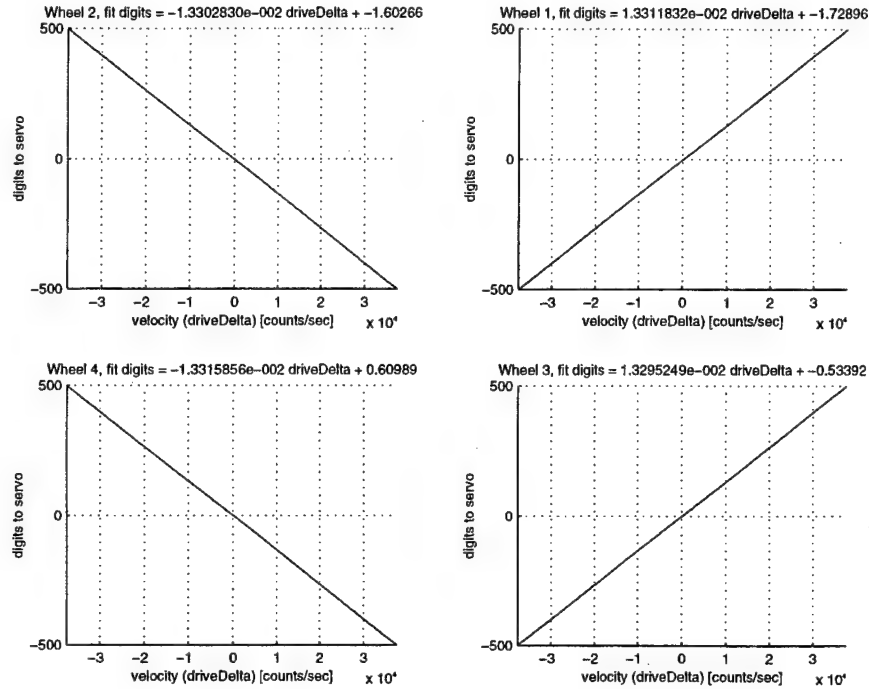
Figure 4.1: Commanded Digits versus Encoder Differences for Free Floating Wheels.
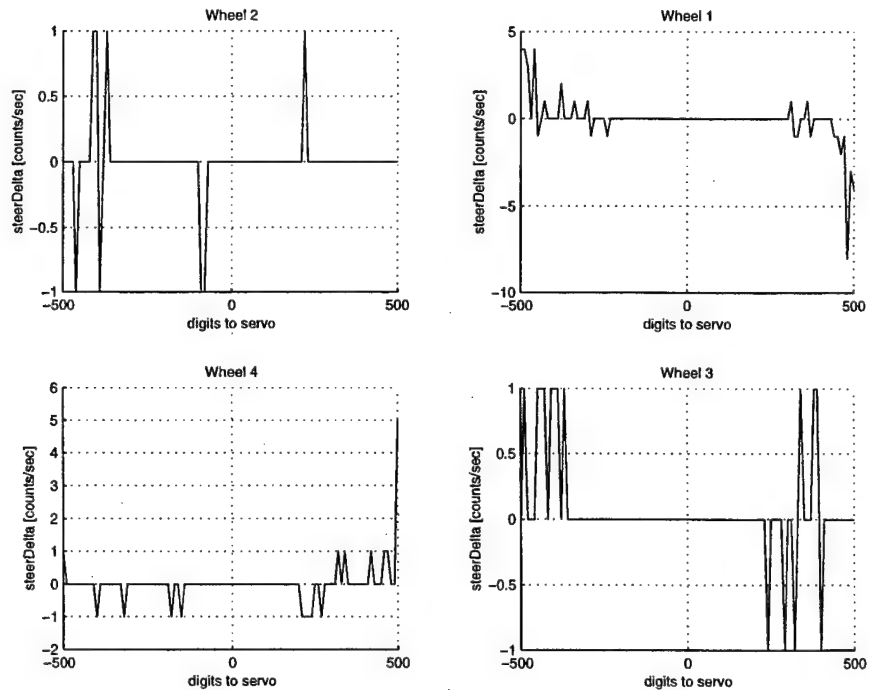
Figure 4.2: Influence of Commanded Drive Digits on Steering Wheels. Plot shows Encoder Differences vs. Commanded Drive Digits for Steering Motors (Steering Motors set to zero).

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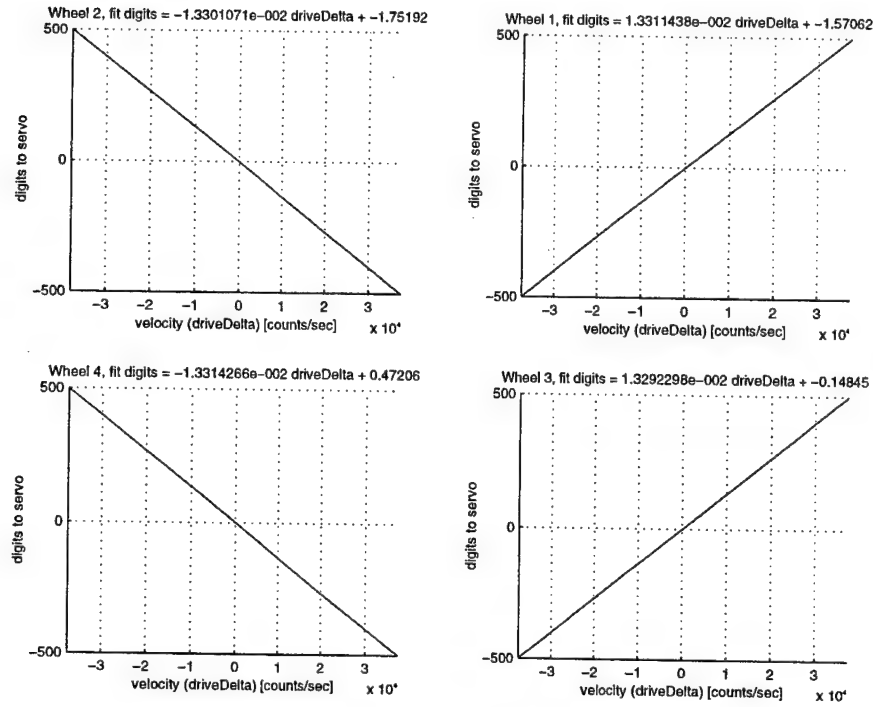
Figure 4.3: Commanded Digits versus Encoder Differences for Vehicle on the Ground.
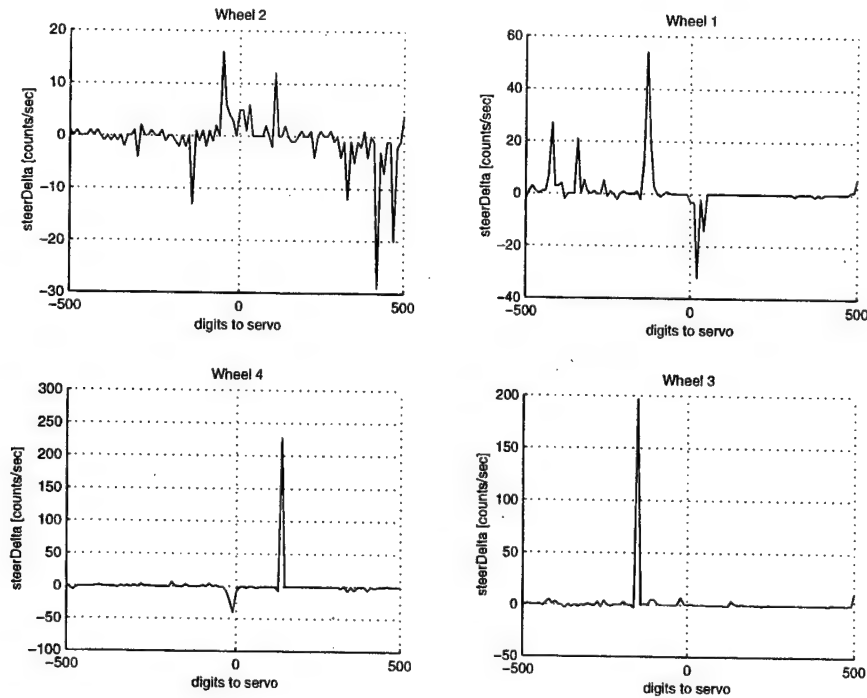
Figure 4.4: Influence of Commanded Drive Digits on Steering Wheels for Vehicle on the Ground. Plot shows Encoder Differences vs. Commanded Drive Digits for Steering Motors (Steering Motors set to zero).

line and a third time with the vehicle lifted off the ground and the wheels rotating free. Despite the changing test conditions, the results were independent from the way the vehicle was suspended. The recorded data for each wheel was fitted in a least square sense by a polynomial of order 1 (a straight line) and the coefficients are given in Table 4.5 where the encoder difference `driveDelta` is given in units of counts per second.

Wheel 1	digit = 0.01331 driveDelta [count/sec] - 1.65
Wheel 2	digit = -0.01330 driveDelta [count/sec] - 1.65
Wheel 3	digit = 0.01329 driveDelta [count/sec] - 0.30
Wheel 4	digit = -0.01331 driveDelta [count/sec] + 0.55

Table 4.5: Relationship between drive encoder difference and commanded servo drive speeds.

It is beneficial to use the relationship digit=f(driveDelta/sec) vice the inverse since for any motion control process, we are given the desired speed (which is directly proportional to the variable driveDelta/sec) and want to obtain the required digit to control the servos accordingly. Using the conversion factor given for driving the wheels (see Table 4.4) and the wheel's radius (which we assume to be equal for all wheels to be 18.9cm) we obtain the conversion from distance travelled to count advances by

$$
\begin{aligned}
1 \text{ count} &= \frac{2\pi}{360 * 290} \cdot 18.9 \text{ cm} = 1.13747 \cdot 10^{-3} \text{ cm} \\
1 \text{ m} &= 87914 \text{ counts}
\end{aligned}
\tag{4.1}
$$

and we finally end up with a handy relationship between velocity [cm/sec] and digits commanded to the servos (the digits are not yet left justified):

Wheel 1	digit = 11.70 v [cm/sec] - 1.65
Wheel 2	digit = 11.69 v [cm/sec] - 1.65
Wheel 3	digit = 11.68 v [cm/sec] - 0.30
Wheel 4	digit = 11.70 v [cm/sec] + 0.55

Table 4.6: Relationship between Velocity [cm/sec] and Commanded Servo Digit (needs further be multiplied by 16 to justify left).

After multiplying the above data by 16 in order to shift it digital wise one nibble to the left, we obtain

Table 4.7 yields the values that can be directly sent to the driving servos. They will already yield the left-justified data sent to the analog output board. Recall that only the upper 12 bit determine the final servo speed. Hence, when driving the wheels, we encounter a discretization error introduced by converting the double valued velocity to 12 bit!

B.   LINEAR MOTION PROFILE

In order to test the sampling results obtained from both, the shaft encoder and the IMU, a simple linear motion profile was implemented in the SRK. The profile is implemented as routine 'linearMotion1()' in the source file 'motor.c' and is shown in Figure 4.5. As it turned out later, this profile was not suitable to obtain reliable data. Hence, a second profile was implemented as routine 'linearMotion2()' and the vehicle's principle behavior is depicted in Figure 4.6. While the vehicle would travel a distance of 4 m in forward direction and return to its start position upon execution of 'linearMotion1()', it would travel for 5/6 of a meter forward and stop for 'linearMotion2()'. However, the vehicles maximum acceleration for the former motion would be $2 \ cm/sec^2$ while for the latter, the vehicle would speed up to $1 \ m/sec^2$ which is quite high!

In the following, the results for the shaft encoders for both motion profiles will be discussed utilizing the motion control procedure as outlined in Chapter II on page 12. The analyzing MATLAB routine 'shaft.m' is for completeness given in Appendix B.5 on page 65.

1.   Linear Motion Profile #1

This motion segment lasts for a total of 70 seconds, after which the vehicle is expected to have returned to its start position. The stop during the period $30sec < t < 40sec$ is utilized to mark the turning position for the vehicle.

Clearly, as Figure 4.8 reveals, the driving angles are off by up to 10 degrees upon completion of the motion program. On the floor, a lateral deviation of approximately 35 cm has been observed. The longitudinal distances traveled came out to be 395 cm for the forward leg and 401 cm for the reverse leg.

Despite the fact that the steering motors are set to zero, there remains interaction between driving and steering. It needs to be determined whether or not this relates to badly adjusted (offset) servo motors or indeed driving interaction. In any case, it is quite evident that feedback is required to provide the desired accuracy for straight motion. The aspects of feedback are not discussed in

Wheel 1	digit = 187.20 v [cm/sec] - 26.4
Wheel 2	digit = 187.04 v [cm/sec] - 26.4
Wheel 3	digit = 186.88 v [cm/sec] - 4.8
Wheel 4	digit = 187.20 v [cm/sec] + 8.8

Table 4.7: Relationship between Velocity [cm/sec] and Commanded Servo Digit.
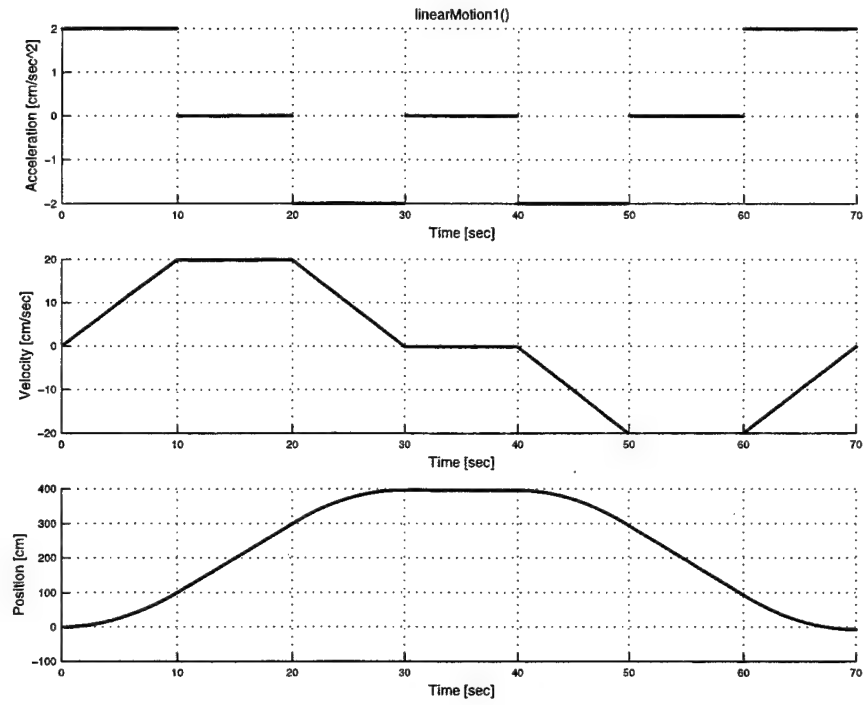
Figure 4.5: Linear motion profile implemented as `linearMotion1()`.
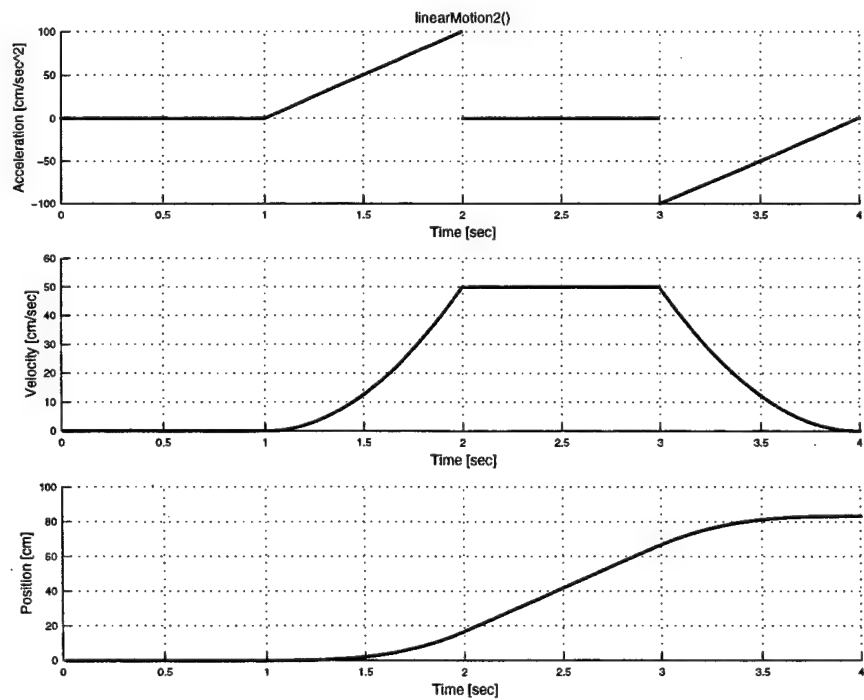
Figure 4.6: Linear motion profile implemented as `linearMotion2()`.
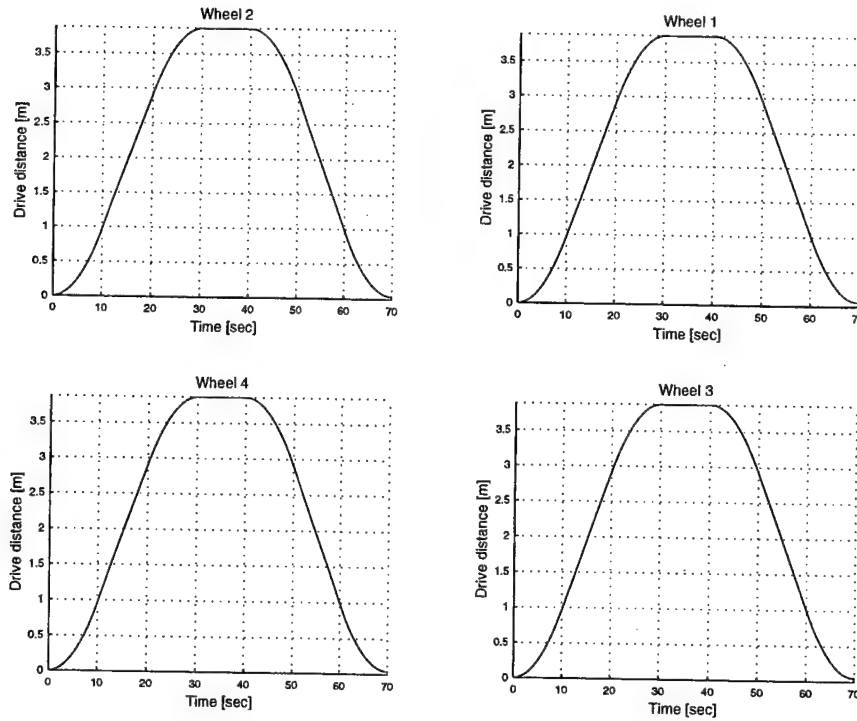
Figure 4.7: Accumulated drive encoder readings versus time for linear motion profile #1.
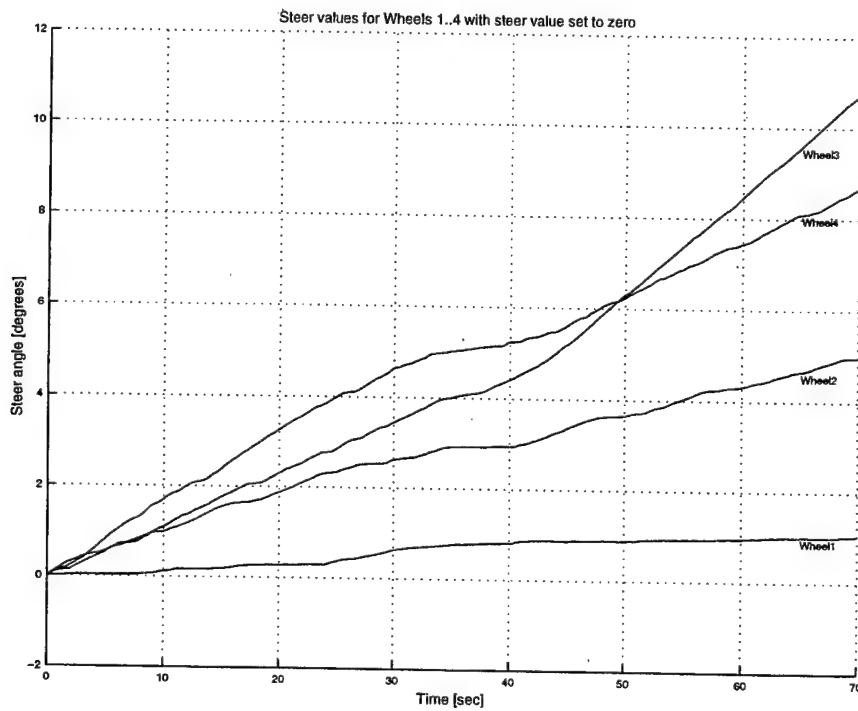
Figure 4.8: Accumulated steer encoder readings versus time for linear motion profile #1.

this thesis. However, Mays/Reid [1] provide a brief discussion about this topic.

2. Linear Motion Profile #2

In order to serve the IMU analysis better, a linear motion profile was needed which provided a greater acceleration for the vegicle. Thus, the linear motion program 'linearMotion2()' has been implemented in the file 'motor.c'. This motion program drives the vehicle over a distance of about 83 cm (5/6 m) within 4 sec. As was for the motion profile #1, the vehicle follows closely the determined path.

Considering the fact that no feedback has been implemented in the motion control programs, it can be concluded that the shaft encoder readings provide sufficient accuracy for determining the planar motion for SHEPHERD under the condition that no slip occurs.

C. UNCERTAINTIES IN MOTION CONTROL

It is quite obvious that the accuracy of the motion control part and the position determination depends on several parameters that may vary over time or that were determined too inaccurate. The main reasons for inaccurate motion control and position determination derived from the shaft encoder readings are

1. Inaccurate sensor parameters relating to the angular position of each motor.
2. Wheel radius not measured correctly or radius changing over time due to wear or changing tire pressure.
3. Data reduction for velocity from double valued data type to 12 bit that are being sent to the servos.

All these factors will eventually degrade the performance of the implemented routines. Hence, there will be ample space for improvement for future work.

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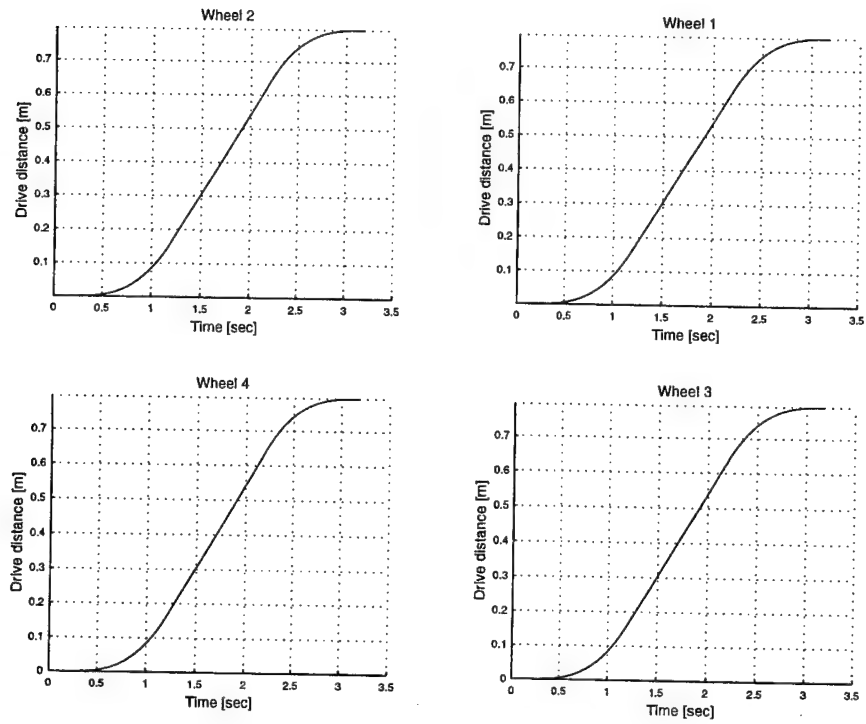
Figure 4.9: Compounded drive encoder readings versus time for linear motion profile #2.
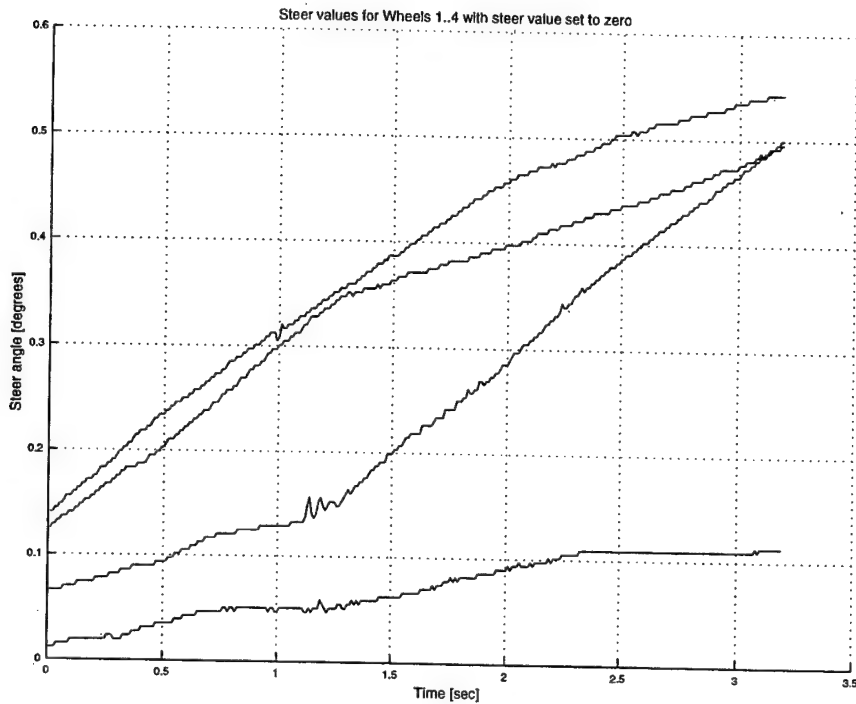
Figure 4.10: Compounded steer encoder readings versus time for linear motion profile #2.

V. INERTIAL MEASUREMENT UNIT

This chapter describes the framework that was implemented on SHEPHERD in an attempt to obtain reliable velocity and position data based on inertial measurements. All source code as it pertains to the implementation of the Inertial Measurement Unit (IMU) is provided in the source file 'imu.c' and listed in Appendix C.1 starting at page 67.

Figure 5.1 shows the vehicle's basic appearance with the four wheels at the corners labelled 1 to 4 and the motion sensor with its three corners marked by a solid dot which span the xy-plane in the body frame {B} mounted on its steel plate. The solid dots on the sensor's casing are just to relate the upside down orientation to the general appearance as given by Figure 5.2.
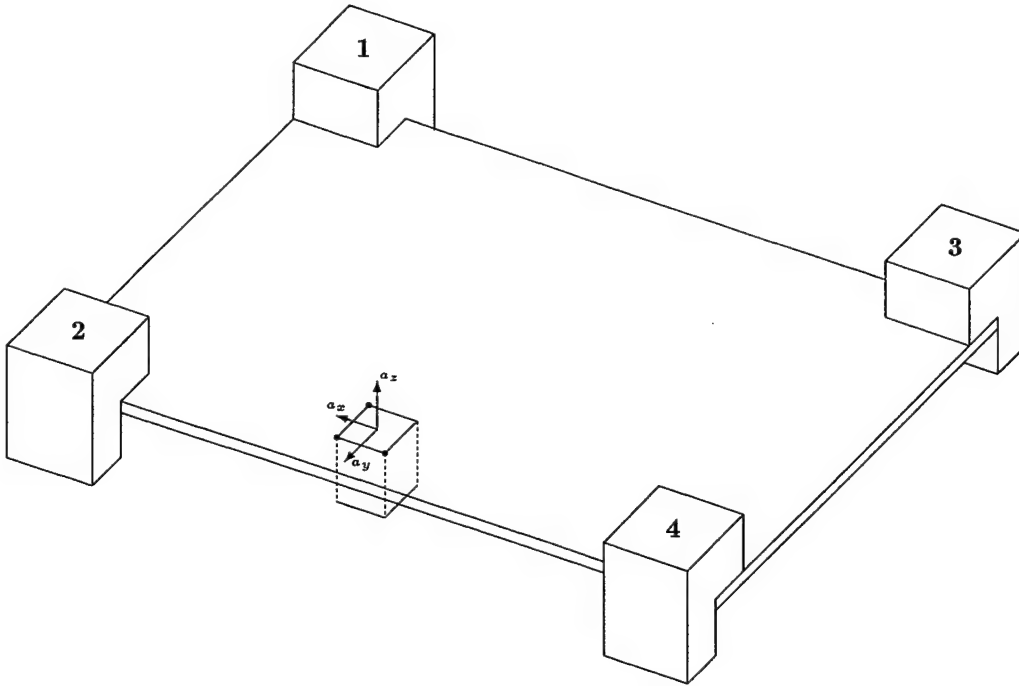
Figure 5.1: Configuration for Shepherd Rotary Vehicle

Due to the particular design of the SHEPHERD Rotary Vehicle, the vertical axes of each wheel are exactly located on the corners of a square of dimension 0.8×0.8 m. The sensor is mounted upside down below the supporting steel plate at the location indicated in Figure 5.1.

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A.   INERTIAL SENSOR

For this project, a four degree of freedom inertial sensor cluster (Solid-State Motion Sensor, Type MotionPak) from SYSTRON Donner, Concord California [8] is being used. It provides three outputs for linear motion measured with servo accelerators (a_x, a_y, a_y) and one output for measuring rotational motion about the z-axis (ω_z). This data comprises a cartesian coordinate system which is shown in Figure 5.2. The dots in the three corners shall help identify the attitude of the sensor as shown in Figure 5.1.
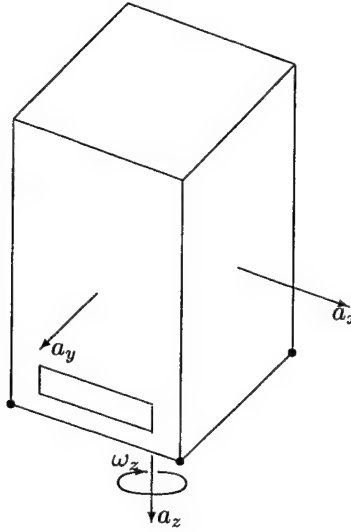
Figure 5.2: Axis orientation for MotionPak Sensor

The MotionPak is customized by the manufacturer for the anticipated dynamic range. Table 5.1 shows most of the specifications as they apply to the model in use.

	x-axis	y-axis	z-axis	
	a_x	a_y	a_z	ω_z
Range	$\pm 2g$	$\pm 2g$	$\pm 2g$	$\pm 50°/sec$
Scale factor	$3.748V/g$	$3.752V/g$	$3.744V/g$	$49.881 mV/(deg/sec)$
Stationary output	0.0 V	0.0 V	+3.75 V	0 V
Bandwidth	869 Hz	925 Hz	869 Hz	75 Hz
Noise (10-100Hz)	1.8 mV_{RMS}	1.8 mV_{RMS}	2.0 mV_{RMS}	3.9 mV_{RMS}

Table 5.1: Operating specifications for MotionPak Model No. MP-G-CQBBB-100, Serial No. 0329 (after Reference [9])

As was already shown by Figure 2.4 on page 8, the analog data provided by the MotionPak IMU is converted into digital data by an A/D-Board interfacing to the VMEBus. The converted

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digital data is transferred from the A/D-Board to the 68040 processor on the TUARUS board via the VMEBus. Figure 5.3 shows how the four analog channels from the MotionPak IMU are actually routed through the A/D-Board to the CPU.
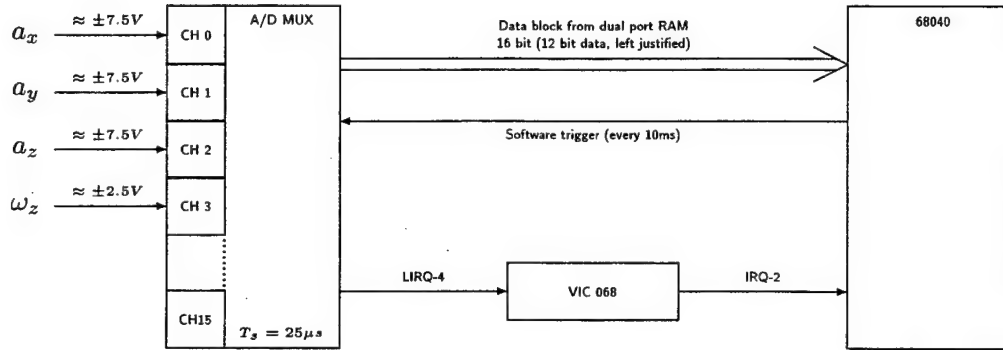
Figure 5.3: IMU Hardware Integration

B. A/D CONVERSION SCHEME

The IMU provides continuous analog data to channels 1 to 4 of the A/D-Board VME9325 [10]. With every 10 ms timer interrupt, a block conversion on the AD-Board is triggered via software command issued by the interrupt handling routine from the 10 ms timer. The AD-Board is configured to multiplex the four input channels every 50 μ sec for a total of 200 samples. Thus, in a consecutive order, each of the four channels are sampled at a sampling rate of f_s=5000 Hz and the digital data is stored sequentially in the A/D-Boards dual-port RAM. Once the block conversion is complete, the A/D-Board will issue an interrupt (see Appendix D.4 on page 93 for the exact interrupt level in use) to 68040 where the corresponding interrupt handler routine analyzeVME9325() preprocesses (filters) the block data and stores it as the most recent data in the global variables

$$a_x \Longrightarrow \text{imuAX}$$
$$a_y \Longrightarrow \text{imuAY}$$
$$a_z \Longrightarrow \text{imuAZ}$$
$$\omega_z \Longrightarrow \text{imuOmegaZ}$$

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which will thus be available for the next motion control cycle to update the actual vehicle motion. The board's status can be observed by means of LED indicator lights at the boards front panel:

Green LED	Red LED	Status
off	on	Board is not initialized
on	on	Board undergoes initialization
off	off	Board is initialized but inactive
on	off	Board is performing A/D block conversions

Table 5.2: Status indicator lights for A/D-Board

At present, the data is merely downloaded via the TAURUSBug 'du0' option (see Appendix D.3) through the CONSOLE port to the Laptop and from there to the UNIX System, where the data was further analyzed using MATLAB. However, for the future, the sampled data would be directly processed by the 68040 processor as outlined above.

One might ask, why was the odd sampling frequency $f_s = 5000$ Hz is being used instead of a more intuitive 10 kHz. A look at the timing diagram Figure 5.4, reveals that the time Δ between the last block conversion (ω_z in block 50) and the start of the next motion control cycle is governed by the sampling frequency: for continuous sampling (e.g., increased block number to transfer), the larger f_s the smaller will Δ be. However, there is a constraint on the minimum length of Δ due to the fact that the sampling block data must be transferred to the TAURUS main memory. This transfer must be done before the next motion control cylce is issued by the 10 ms timer interrupt. This rule must be closely followed, otherwise a loss of sampling data might occur.
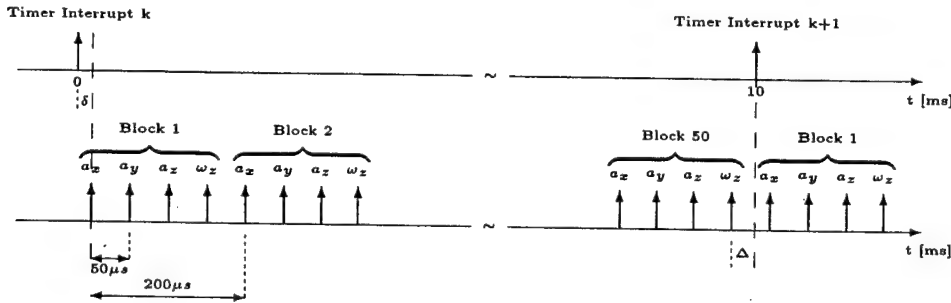
Figure 5.4: Timing Diagram for A/D-Board

The A/D-Board maps a preset input span of $\Delta = 20$ V for a differential input range of $\pm$ 10 V into n=12 bit bipolar two's complement data left justified in a 16 bit word. The value of -2048 relates to an analog input equvalent of -10 V $\leq x_{analog} <$ -9.99512 V. Likewise, the digital output

of 2048 relates to $0 \text{ V} \leq x_{analog} < 0.00488 \text{ V}$. The stepsize is given by $\delta = \frac{\Delta}{2^n} = \frac{20V}{4096} = 4.88 \text{ mV}$. To make use of the maximum range available, the board provides a variable gain to amplify the input signal by factors G=1, G=2, G=4, or G=8. Moreover, we need to scale the data by the appropriate scaling factors S for each channel which are given in Table 5.1. Thus, for a given channel with gain G and scaling S, we obtain the analog equivalent of the data by shifting the digital value $x_{digital}$ by 4 bit to the right (which is equivalent to a division by 16) and than re-scale it according to:

$$x_{analog} = \frac{\Delta}{2^n \, G \, S} \left(x_{digital} - 2048 \right) \qquad .$$

Using the scaling factors given in Table 5.1 we end up with the units of [g] for a_x, a_y, and a_z and [degrees/sec] for ω_z. Expressing the linear acceleration a in terms of the gravitational acceleration g rather than in SI-units of $[m/sec^2]$ turns out to be beneficial if we need to find the Euler angles and a suitable representation for it in the reference frame {R}.

C.   SCHEME FOR DATA ANALYSIS

Accelerometers sense the sum of the gravitational acceleration $\vec{a}_g$ and the linear acceleration $\vec{a}$ which is due to an external force applied to the body in the body frame {B}

$$^B\vec{a}_m \;\; = \;\; {}^B\vec{a} + {}^B\vec{g} \tag{5.1}$$

which relates to the reference frame {R} as

$$^R\vec{a}_m \;\; = \;\; {}^R\vec{a} + {}^R\vec{g} \qquad . \tag{5.2}$$

In both frames, g is the acceleration of gravity derived from Keplerian physics for two body motion theory between the Earth and a body. Usually, g is a function of the distance r between the center of masses of the two bodies and can be computed with

$$g = \frac{G \, M}{r^2}$$

with the constants G and M as described in Appendix A. For a body at the Earth's surface, $g \approx 9.81 \; m/sec^2$ and usually, the variation in height for small changes can be neglected. Therefore we will not concern ourselves with a variable g and assume that $g = 9.81 \; m/sec^2$.

In the following, we will devise a scheme to eliminate the undesired gravity components in our measurement data. Therefore, we will have to focus on the stationary vehicle first, that is, the only acceleration acting on the vehicle in frame {B} will be the Earth gravity. Moreover, we know that in the reference frame {R}, the acceleration due to gravity has only a +z-component whereas

in {B} we would usually encounter gravitational components in each of the principal axes unless the sensor is perfectly aligned with frame {R}:

$$^{R}\vec{g} = \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \quad \text{and} \quad ^{B}\vec{g} = \begin{pmatrix} {}^{B}g_x \\ {}^{B}g_y \\ {}^{B}g_z \end{pmatrix}$$

subject to the constraint that $g = \sqrt{{}^{B}g_x^2 + {}^{B}g_y^2 + {}^{B}g_z^2}$. To express frame {B} in terms of frame {R} we make use of the rotation matrix as outlined in the previous sections and given by Equation 3.2:

$$^{R}\vec{a}_m = {}^{R}_{B}\mathbf{R} \; {}^{B}\vec{a}_m$$

We therefore do need to get the Euler Angles (roll, pitch, and yaw) as defined on page 17. We make us of the fact that the acceleration of a stationary sensor as measured in {R} should only display the gravitation:

$$^{R}\vec{a}_m = \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} = {}^{R}R_Z(\psi) \; {}^{R}R_y(\phi) \; {}^{R}R_X(\theta){}^{B}\vec{a}_m \qquad .$$

Solving for $^{B}\vec{a}_m$ yields

$$^{B}\vec{a}_m = {}^{R}R_X^{-1}(\psi) \; {}^{R}R_y^{-1}(\phi) \; {}^{R}R_Z^{-1}(\theta) \; {}^{R}\vec{a}_m \qquad .$$

We recall the identity given in Equation 3.1 on page 16 and rewrite the above equation in terms of the transpose of each rotation matrix:

$$^{B}\vec{a}_m = {}^{R}R_X^T(\psi) \; {}^{R}R_y^T(\phi) \; {}^{R}R_Z^T(\theta) \; {}^{R}\vec{a}_m \qquad . \tag{5.3}$$

For any measurement vector $^{B}\vec{a}_m$ and the related vector $^{R}\vec{a}$ in frame {R}, Equation 5.3 together with the definitions for the rotation matrices Equation 3.3, Equation 3.4 and Equation 3.5 given on page 17 provides us with a system of three equations from which we can determine the Euler Angles. In particular, we are easily able to determine the Euler angles as a function of the measurement $^{B}\vec{a}_m$:

$$a_{xm} = -g \, sin(\phi) \tag{5.4}$$

$$a_{ym} = g \, sin(\theta) \, cos(\phi) \tag{5.5}$$

$$a_{zm} = g \, cos(\theta) \, cos(\phi) \qquad . \tag{5.6}$$

We recognize that for the stationary data, the acceleration measured in {B} does not depend on the yaw angle ψ which is directly related to the heading of the vehicle (in order to obtain the heading, we,

of course, would need to have a compass at hand). Solving the above system for the two remaining Euler angles yields the following equations:

$$\phi \;=\; -arcsin\left(\frac{a_x}{g}\right) \tag{5.7}$$

$$\theta \;=\; arcsin\left(\frac{a_y}{g\,cos(\phi)}\right) \tag{5.8}$$

or alternatively for θ

$$\theta \;=\; arcsin\left(\frac{a_y}{\sqrt{a_y^2 + a_z^2}}\right) \;. \tag{5.9}$$

We see that the last two equations both yield a solution for θ. Depending on the accuracy of our measurements and the accuracy of the desired math functions we have implemented so far, we may prefer the one to the other. Since the Sensor's output data is already scaled with respect to g, the Earth's gravity (see Table 5.1), we may prefer the former and discard Equation 5.9. This is reflected in the MATLAB listing for 'getdata.m' where the data is arranged accordingly.

Based on the theory pertaining to the inertial measurement sensor as outlined above, the following scheme to obtain the position data for the vehicle is proposed:

1. Sample stationary data (as is usually the case if one starts up the vehicle) in frame {B} for a certain period of time.

2. Filter the data with an appropriate lowpass filter.

3. Compute the Euler angles θ and ϕ.

4. Transform the data from frame {B} to frame {R} using the rotation matrices given by Equation 3.2, use arbitrary yaw angle ψ.

5. Subtract the acceleration due to gravity acting on the vehicle to obtain the sole acceleration due to a specific force given in frame {R}.

6. Integrate the data in a suitable way to find the velocity and position vector of the vehicle.

D. INTEGRATION TOOLS

In our analysis of the inertial measurement sensor, we will have to integrate the data in order to arrive at the velocity vector. There are many integration methods available for integrating discrete data. For equispaced, discrete data, most of the more commonly known integration formulas such as the Trapezoidal rule, Simpson's Rule, ... are based on the Newton-Côtes Integration Formulas ([11],[12]). Given a set of values $f(x_i)$ for equispaced $x_i = a + ih \; \forall \; i = 0 \ldots n$ with $h = \frac{b-a}{n}$, the

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integral of $f(x)$ on the interval $[a, b]$ can be approximated by

$$\int_a^b f(x)\, dx = \int_a^b P_n(x)\, dx$$

where $P_n(x)$ is the Lagrangian polynomial that passes through all the points x_i and the interval $[a, b]$ is covered by the (n+1) equidistant points x_i. $P_n(x)$ is given by

$$P_n(x) = \sum_{i=0}^{n} f(x_i)\, \alpha_i$$

where α_i is given by

$$\alpha_i = \prod_{\substack{k=0 \\ k \neq i}}^{n} \left(\frac{x - x_k}{x_i - x_k} \right) \qquad .$$

If we let $x = a + hs$ the above integral for $P_n(x)$ reduces to a simple sum

$$\int_a^b P_n(x)\, dx = h \sum_{i=0}^{n} f(x_i)\, \alpha_i = \frac{b-a}{ns} \sum_{i=0}^{n} \sigma_i f(x_i) \qquad . \tag{5.10}$$

The values for ns and σ_i can be computed given the above relations. However, we will not concern ourselves with this issue and state the results for the first few parameters:

n	ns	σ_i	Commonly known rule
1	2	1 1	Tapezoidal
2	6	1 4 1	Simpson's 1/3
3	8	1 3 3 1	Simpson's 3/8
4	90	7 32 12 32 7	
5	288	19 75 50 50 75 19	
6	840	41 216 27 272 27 216 41	

Table 5.3: Newton-Côtes Formula Parameters

Some of these formulas are being implemented in the function 'integral.m' on page page 65 and used for integrating the acceleration data. The analysis in the following sections will discuss which formula shall be preferred to the others.

E.   DATA FILTERING AND COMPUTATION OF POSITION VECTOR

Several recordings for stationary data have been taken. In the process of obtaining the position vector for the vehicle we would expect that starting, say from an initial position $(0, 0, 0)_{\{R\}}$, this should not vary much as time passes by.

Initially, the sampling scheme was such that each channel of the IMU was sampled at a sampling rate of 100 Hz with every 10 ms timer interval. Later on, this has been changed to a sampling rate of 5000 Hz as shown in the timing diagram Figure 5.4 on page 34.

1.   Stationary Data Analysis

The data collected for the stationary data analysis in this subsection has been sampled prior to changing the sampling frequency from 100 Hz to 5000 Hz. Thus, this is reflected in the data presented in this subsection. In addition, the IMU at this stage was not yet mounted to the vehicle and the orientation of the axes was such that the sensors z-axis pointed up instead of down as shown in Figure 5.1. Figures 5.5 to 5.10 show typical results obtained. They show data recorded and processed for a stationary vehicle with file 'imu.m' (see Appendix B.1 on page 59). The data was recorded on the fifth floor of Spanagel Hall with the sensor titled by a significant amount which was not further specified.

As can be seen from Figure 5.6, the linear components (a_x, a_y, and a_z) contain distinct sinusoidal components at $f = 20Hz$ and $f = 40Hz$. The origin of this behavior still needs further examination. However, it seems not to be related to the block sampling interval of T=10 ms, rather than to vibrations inherent in the building. These sinusoidal components can not be beneficial to the performance of our compuations. Therefore, we have to eliminate the residues by some suitable filtering technique.

In the time domain (Figure 5.5), we see the effect due to the A/D sampling process: the sampled data obtained through the A/D Board truly displays the characteristics for discrete-time signals. Moreover, since the sensor was titled, the data will reflect the values according to this orientation relative to frame {R}. Thus, the next step involves computation of the Euler angles and transforming the data into frame {R} using the results obtained in Equation 3.2. Now, follwoing the transformation the data for a_x and a_y should ideally go to zero (at least in the mean). The result is shown in Figure 5.7 with its Fourier spectrum given by Figure 5.8.

In fact, the acceleration for a_x and a_y is almost zero whereas the acceleration for a_z is almost -1.0 g (the DC component is not shown in the frequency spectrum. The negative sign for this data set is due to the fact that the sensor's z-axis pointed down. The final step is to obtain the velocity and the position by integrating the acceleration once or twice, respectively. The velocity is shown in Figure 5.9. As can be seen from the plot, the velocity in x- and z-direction pretty much approaches steady-state after about 3 sec of recording whereas the velocity in y-direction approaches steady state after about 10 seconds (eventually, a longer recording needs to be taken to verify this statement). As for the position vector, which is shown in Figure 5.10, we see that during the first second the error is small and the position remains pretty much zero. However, as the velocity assumes its steady state, the position displays a linear behavior. Therefore, based on the stationary analysis, it is advisable to update (reset) the navigation solution based on the IMU at least every second. Even better, if
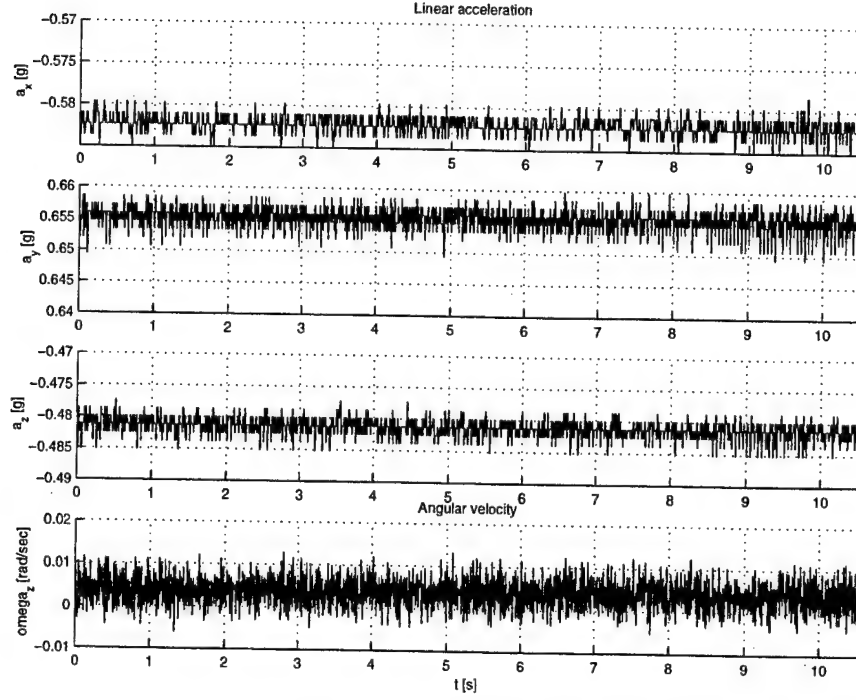
Figure 5.5: Time domain behavior for linear acceleration and angular velocity for the stationary and tilted IMU as measured by the A/D-Board (normalized to units [g]) in frame {S}.
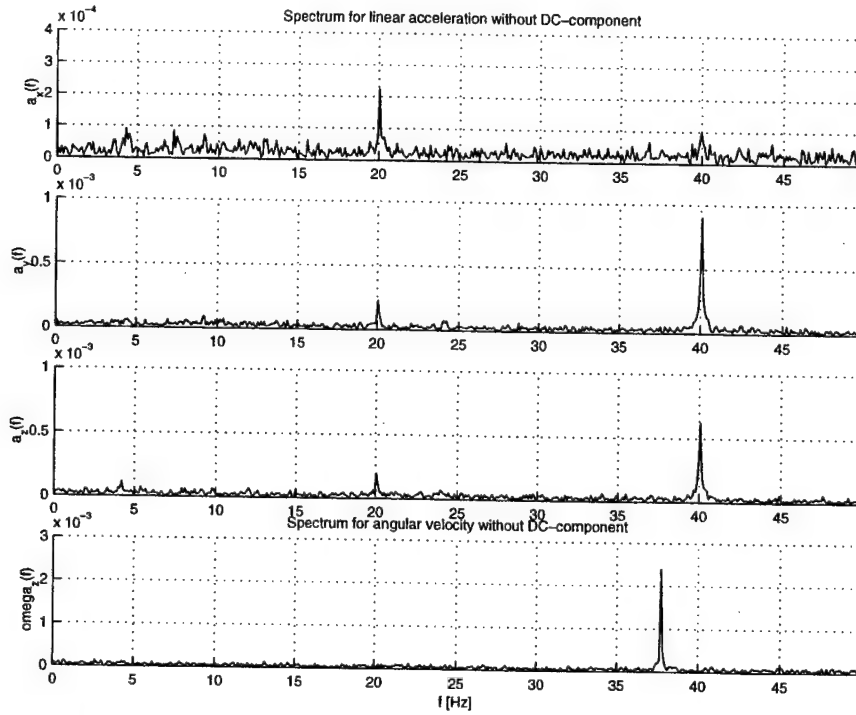
Figure 5.6: Fourier spectrum for linear acceleration and angular velocity for the stationary and tilted IMU as measured by the A/D-Board (normalized to units [g]) in frame {S}.
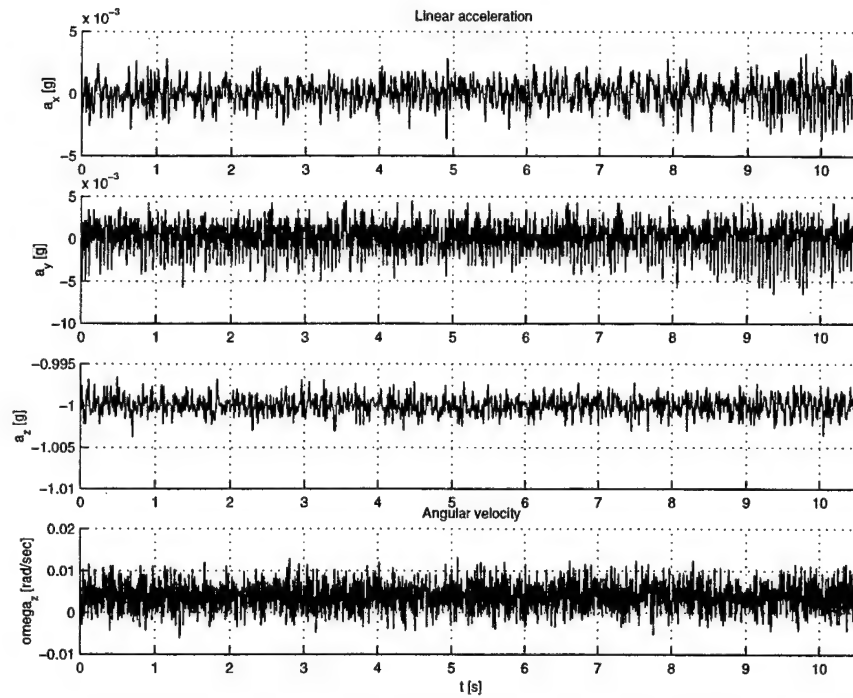
Figure 5.7: Time domain behavior for linear acceleration and angular velocity for the stationary and tilted IMU as measured by the A/D-Board (normalized to units [g]) in the reference frame {R}.
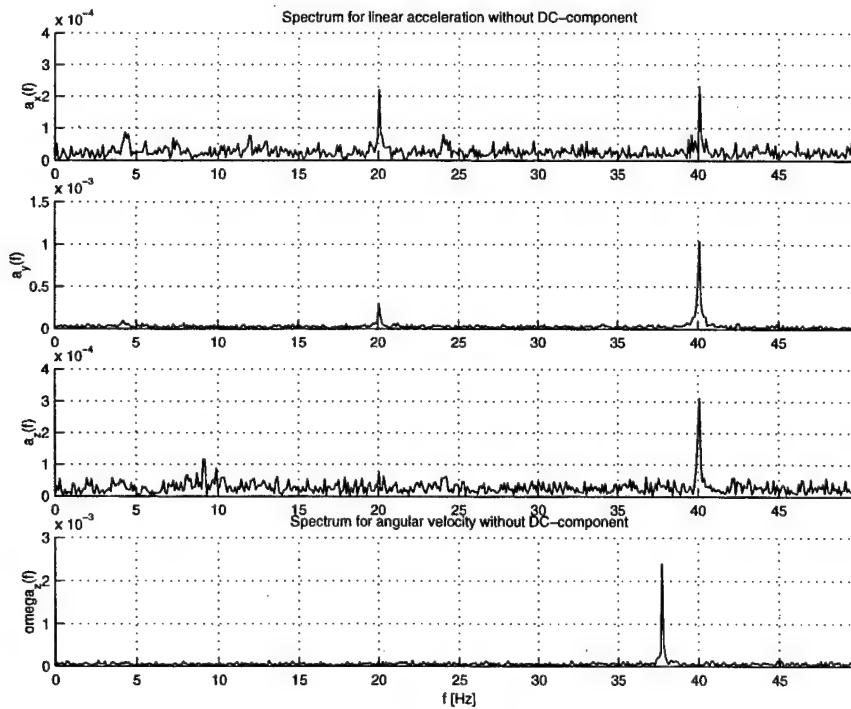
Figure 5.8: Fourier spectrum for linear acceleration and angular velocity for the stationary and tilted IMU as measured by the A/D-Board (normalized to units [g]) in the reference frame {R}.

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the Euler angles which represent the attitude of the vehicle could be determined continuously and in accordance to the updated Euler angles, new rotation matrices would have to be determined on a regular basis.

2.   Non-stationary Data Analysis with Profile #1

In the sequel, we will analyze data sampled at a sampling frequency of $f_s = 5000$ kHz according to the timing diagram depicted in Figure 5.4 from an IMU that is mounted on SHEPHERD as shown in Figure 5.1. First, in order to correlate the sampled data to the actual motion of the sensor/vehicle, the same linear test motion profile as introduced in Chapter IV and shown in Figure 4.5 on page 27 was being utilized. Due to the vast amount of data that had to be analyzed (a recording for 70 sec at a sampling frequency of 5000 Hz on four IMU channels comprised a mere 2.8 MByte!) the analysis was performed on segments of data in order not to exploit the limits of computational power. In particular, to enhance the performance of the built in MATLAB Fourier transform function, segments contained 65536 samples, which is a power of two (2^{16}).

Figure 5.11 depicts the linear acceleration as determined by the IMU. Despite the fact that the linear motion profile was only along the x-axis of the vehicle, the sensor seemed not to distinguish between the channels. All three components display some sort of noise and the signals do not at all seem to be related to the actual motion profile.

The detailed analysis of the a_x-channel is given in Figure 5.12 and 5.13 for the time frame $0 < t < 13sec$. Figure 5.12 shows that the original data is distorted throughout the entire frequency range. Moreover, the time signal does not display the expected behavior according to the true motion profile. Instead, the oscillations increase in amplitude as time advances. To reduce the noise, an elliptic filter has been used to attenuate the noise in the stopband. The software filter, implemented using MATLAB's built in signal processing functions, had the following specifications:

1. Passband from $0 \ldots 20$ Hz with max. attenuation of 0.1 dB
2. Stopband from 50... Hz with min. attenuation of 80 dB

Other filters such as Chebychev and Butterworth filters were also being tested. None of these filter types showed a significant improvement of the data. The only advantage Butterworth or Chebychev filters have compared to Elliptic filters is a better phase linearity in the passband. On the other hand, and most important for an implementation where computation time is scarce, Elliptic filters are most efficient since they yield the smallest-order filter for a given set of specifications [14].
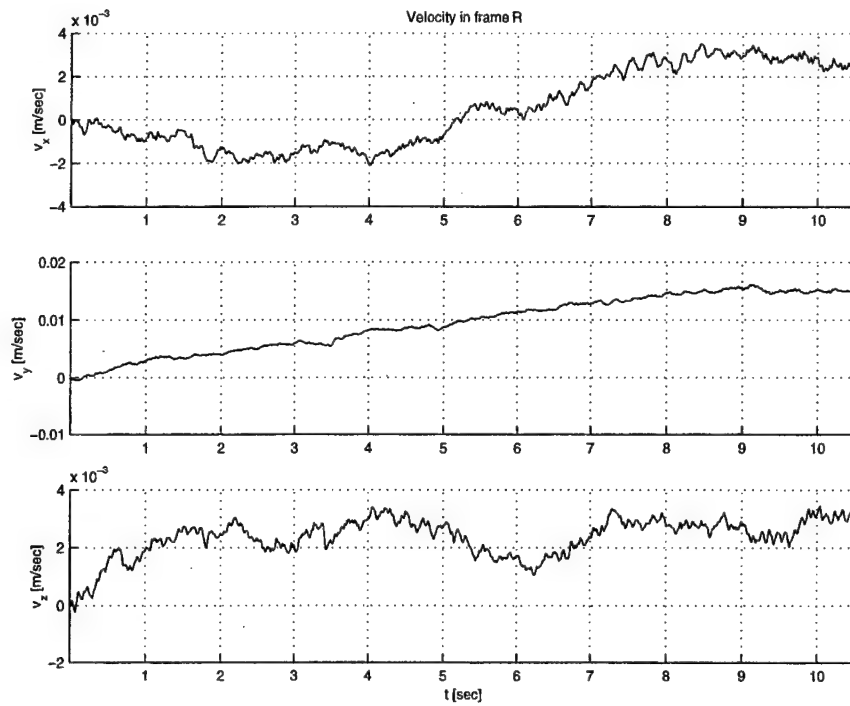
Figure 5.9: Velocity data integrated from the linear acceleration in frame {R}.
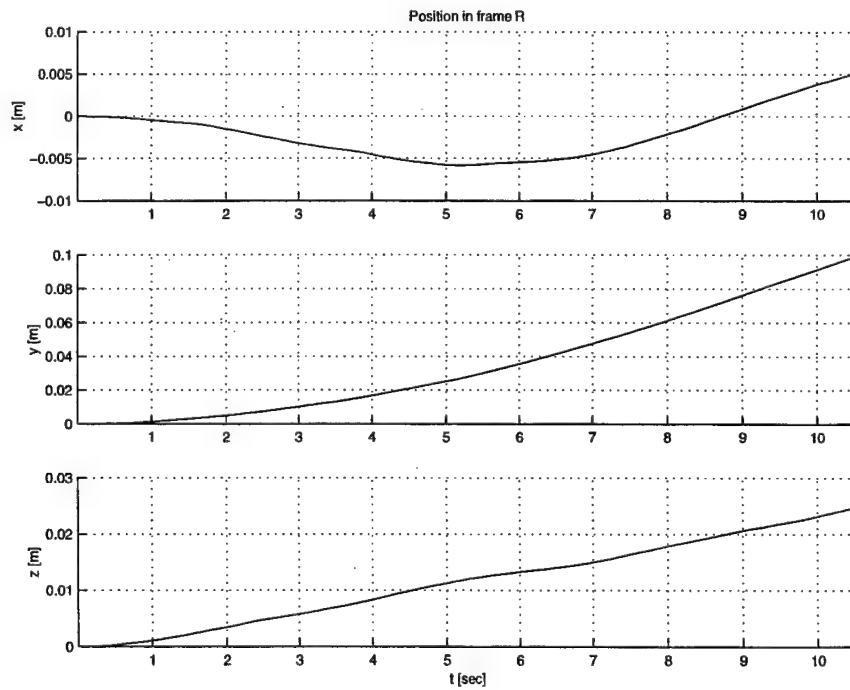
Figure 5.10: Position integrated from the velocity in frame {R}.
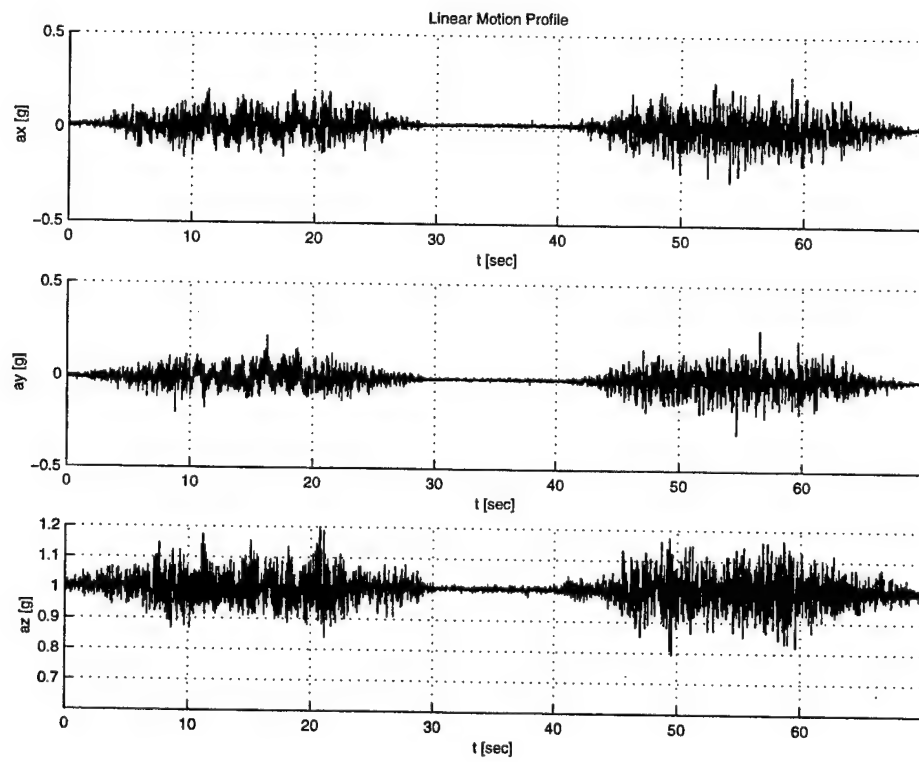
Figure 5.11: Linear Acceleration measured by all three channels of the IMU for Linear Motion Profile #1.
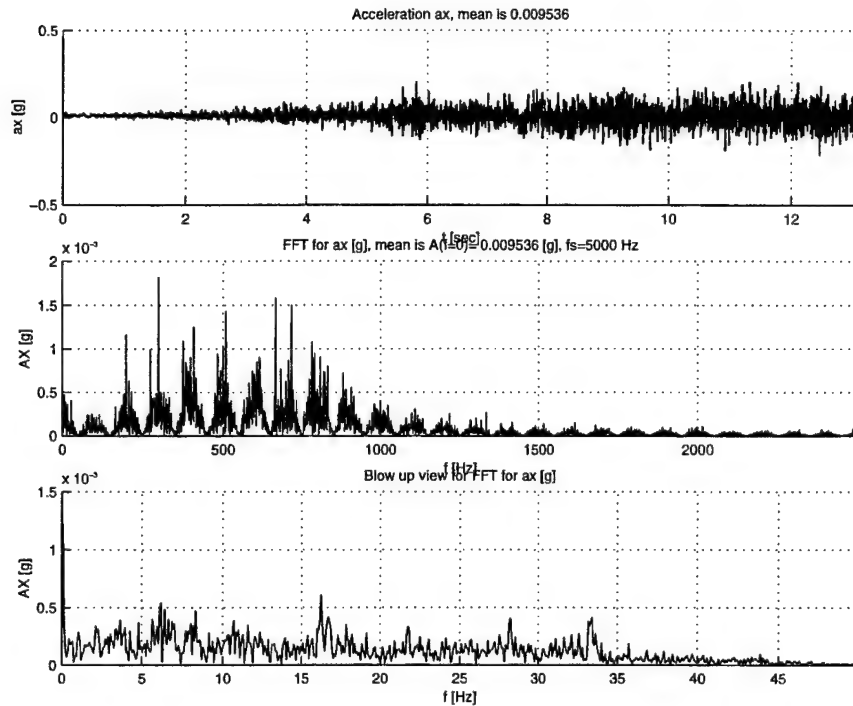
Figure 5.12: Analysis of linear acceleration ax as measured by the IMU.
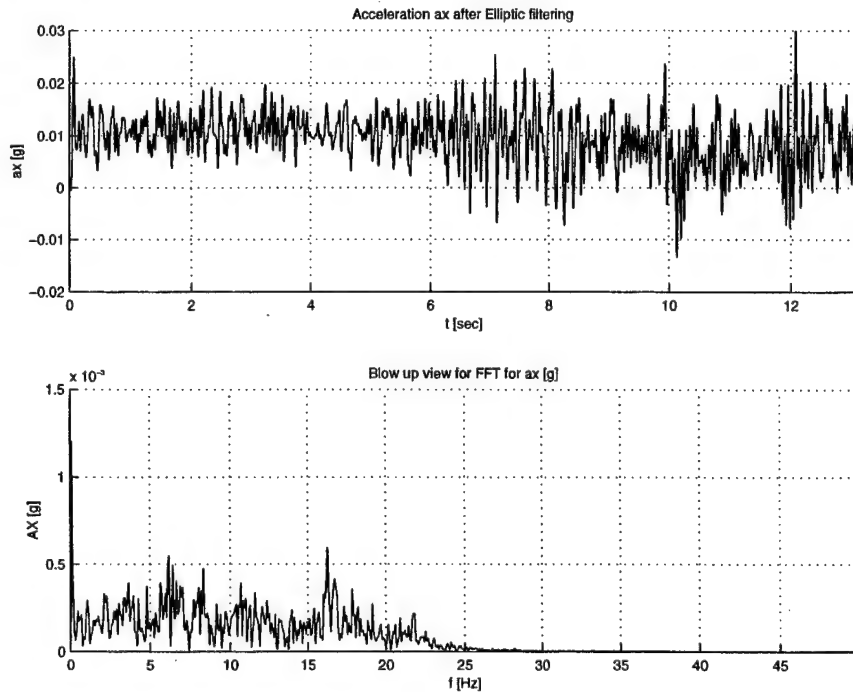
Figure 5.13: Analysis of linear acceleration ax after data has been filtered by a 6th order elliptic filter with passband edge at 20 Hz and Stopband edge at 50 Hz.

The results, as depicted in Figure 5.13 do not look too promising. Althought the filter achieved to smooth the data and reduce the noise, it could not ensure that the acceleration would show any transition at t=10sec. Recall that according to the true profile, the acceleration should be zero starting with t=10sec. The only reason that can be attributed to this fatal behavior is the dynamic input range of the A/D-Board: operating the accelerometer at a maximum linear acceleration of $a_x = 0.02 m/sec^2$ (which is only ≈ 0.002 g) we utilize only a voltage span from -7.6 mV to +7.6 mV that is fed into the A/D-Board. Even if the maximum gain of 8 is used to amplify this signal, the amplitude would never exceed ≈ 62 mV which comprises a mere four digits in the digital output range.

3.   Non-stationary Data Analysis with Profile #2

It was anticipated that, for the second motion profile as shown in Figure 4.6, results for the measured acceleration would improve. The maximum acceleration was set to be 1.0 m/sec^2 with the maximum velocity reached by the vehicle to be ≈ 0.5 m/s. The sampled data for all three linear acceleration channels is shown in Figure 5.14. The plot reveals strong interaction between all three channels. One goal would be to get rid of these interferences by means of a suitable filter technique. For the time being, we focus on the a_x-channel. The time and frequency behavior for the x-channel is depicted in Figure 5.15. Strong harmonic components influence the overall performance and a similarity to the actual motion can not be found.

Upon filtering with an elliptic filter of order 6, the recorded data can somewhat be related to the true motion. However, since the sharp edges in the ideal acceleration profile (Figure 4.6) result in high frequency components of the signal, these edges can not be recognized by the IMU (the cutoff frequency for the linear accelerometers is around 900 Hz, see Table 5.1. Nonetheless, the questions remains: would this be suffice to compute the velocity? We refer to Figure 5.16 and see that the velocity does in principle follow the curve depicted by the ideal motion profile Figure 4.6. As soon as the recognizable motion kicks in, the velocity seems to be distorted by an offset in the acceleration data (rather than assuming a=0 on the interval $t \in [2, 3]$ sec).

4.   Non-stationary Data Analysis with Profile #3

To get rid of the lowpass constraint, a third motion profile has been developed. The profile is shown in Figure 5.17.

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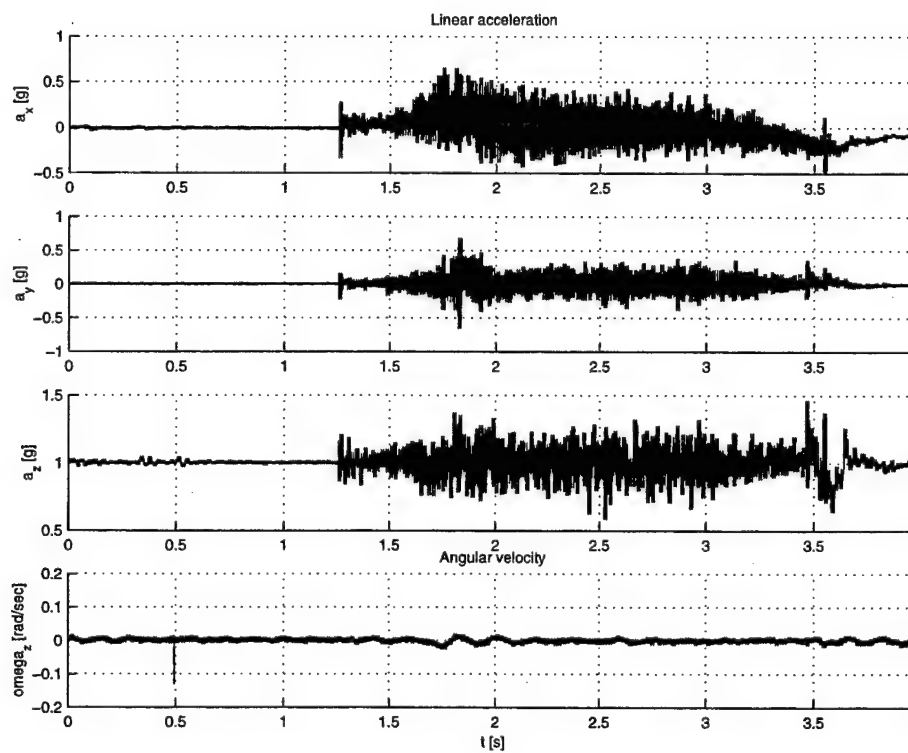
Figure 5.14: Linear Acceleration and angular velocity ω_z relative to frame {R} measured by the IMU for Linear Motion Profile #2.
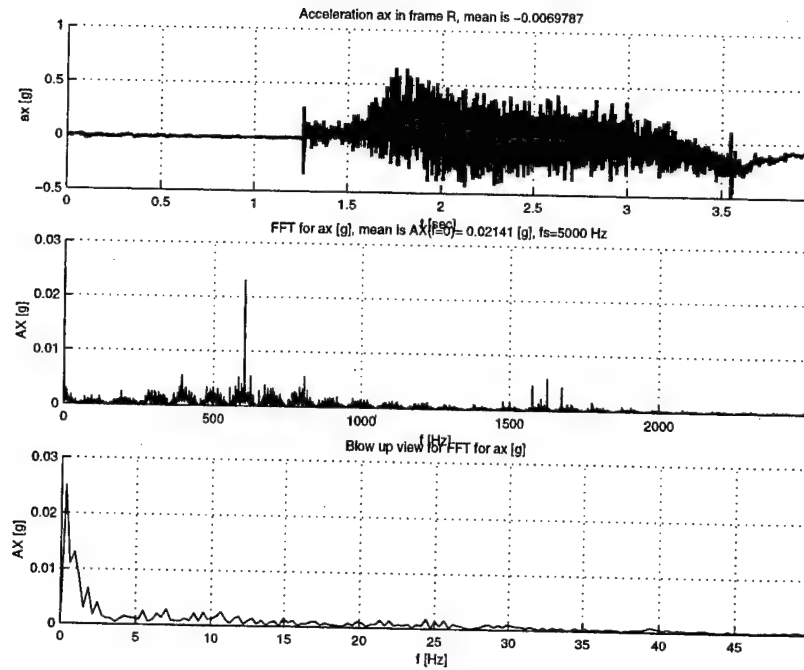
Figure 5.15: Analysis of linear acceleration ax as measured by the IMU.
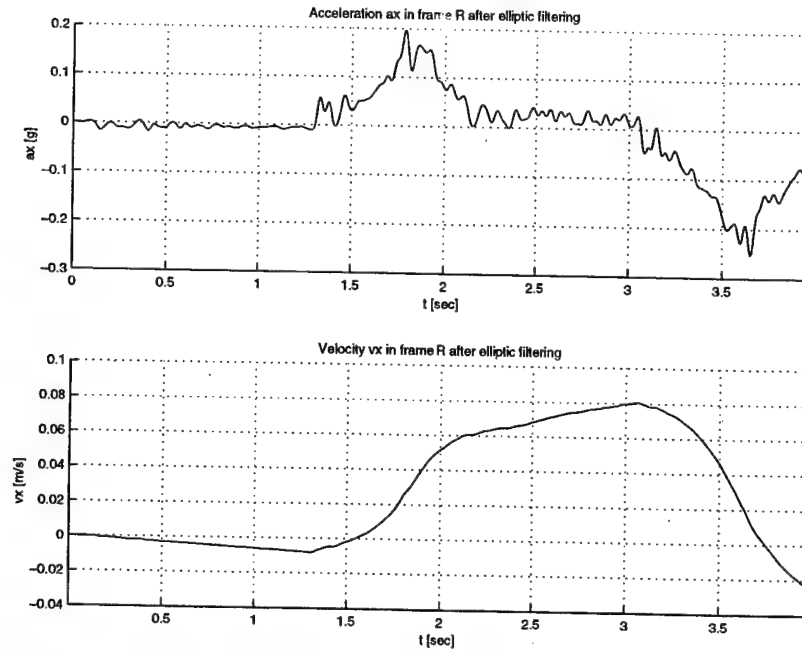
Figure 5.16: Analysis of linear acceleration ax after data has been filtered by a 6th order elliptic filter with passband edge at 20 Hz and Stopband edge at 50 Hz.
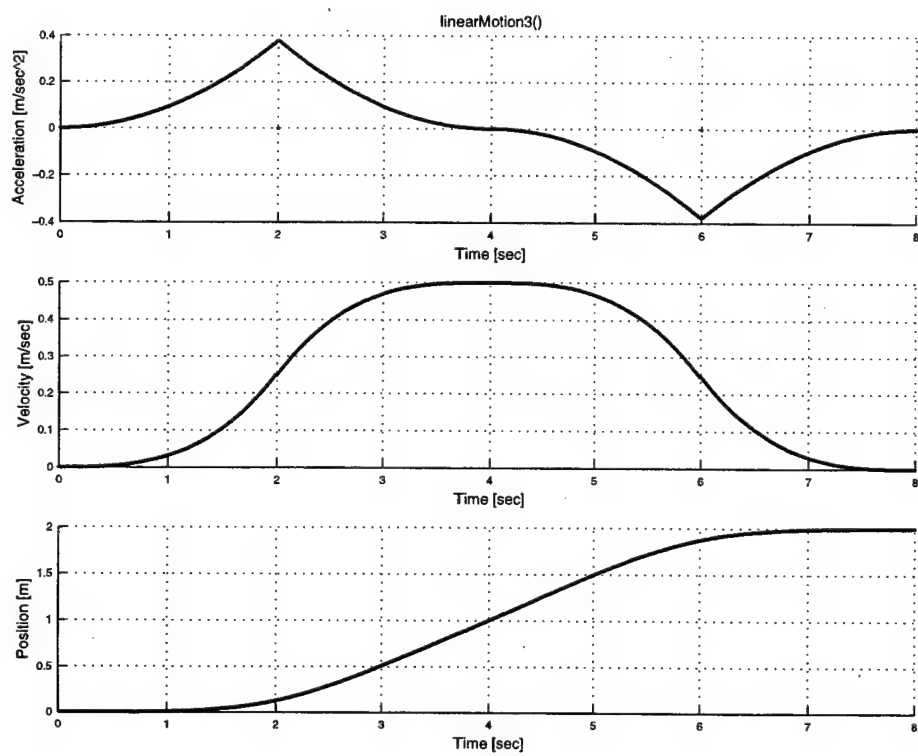
Figure 5.17: Linear Motion Profile #3.

Clearly, this motion should only contain low frequency components. As was the case for the other two motion profiles, the IMU senses noise in all three channels even though the motion takes place only in the sensors x-direction.

F.   SUMMARY

Based on the results obtained from the linear motion profiles #1 .. #3 the following conclusions for the implementation of the inertial measurement unit can be drawn: First, the IMU data sampled off the IMU needs to fit appropriately in the A/D-Boards input range. As a crude rule of thumb based on the observations made in this Chapter, the time average of the acceleration signals to be A/D-converted (this may include any additional gain) should be at least 1/10 th of the max. allowable input amplitude of the A/D-Board (e.g., at present, the max. input is $\pm$ 10 V, the input signal should be at least 1 V in magnitude). A more detailed analysis is required in this respect. Probably the most effective solution would be to utilize MotionPak Accelerometers (QFA7000) with current output rather than voltage output. In this case, the output could be scaled by the user to especially lower 'g' limits by means of variable scaling resistors (see [13] for more information). Probably the most significant shortfall in the design of the vehicle was determined to be the variable suspension of the vehicle's wheels. Whenever the vehicle accelerates by a significant amount, the vehicle's steel platform may tilt. This change of attitude will be recognized by the IMU but can not be attributed to a change of the vehicle's main body attitude and thus to a change of position in 3D space.
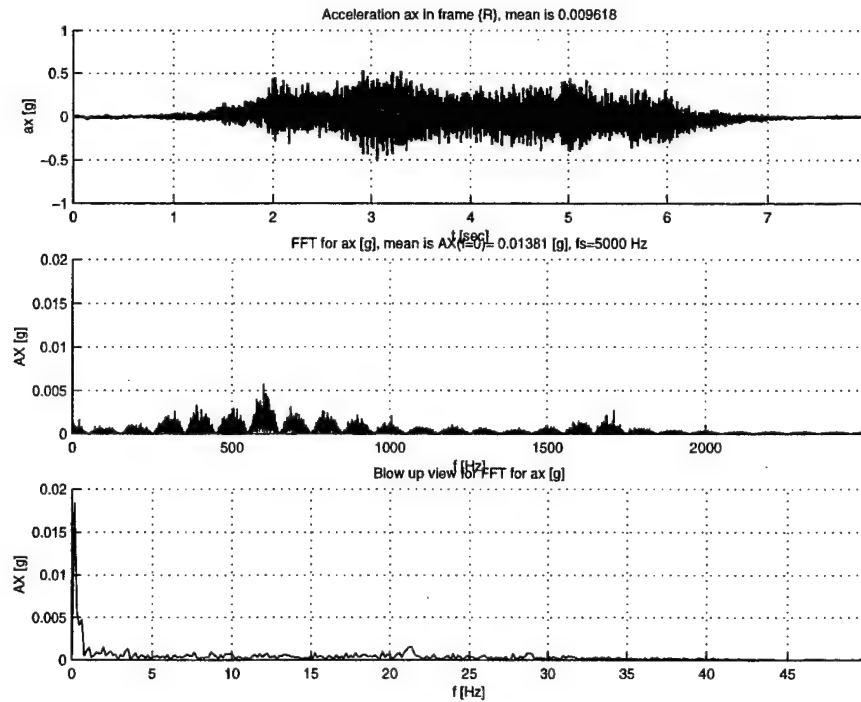
Figure 5.18: Analysis of linear acceleration ax as measured by the IMU.
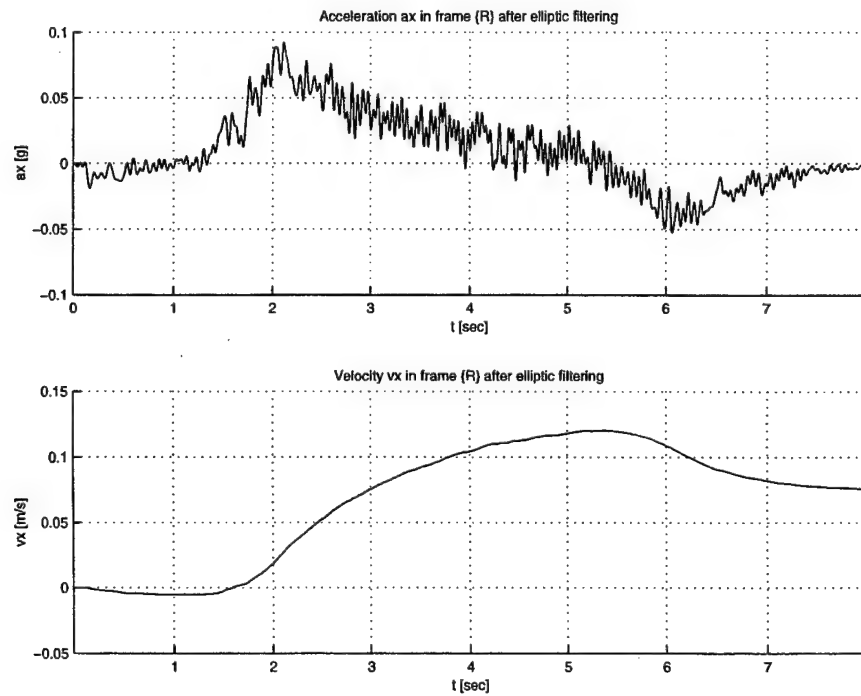
Figure 5.19: Analysis after Elliptic Filtering (6th order filter) with passband edge at 20 Hz and Stopband edge at 50 Hz.

VI.   SENSOR FUSION

Having developed the two independent navigation components in the previous Chapters, it was anticipated to fuse the data provided by both systems to further improve the accuracy of the navigation system. However, since the performance of the IMU does not yield any reliable motion data, sensors fusion at this point of time is obsolete. Some literature research has been done to obtain a hint as to how to fuse the data. Almost all papers related to sensor fusion utilize the extended Kalman filter. Welch [16] provides a decent introduction in Kalman filtering. Nonetheless, it is anticipated that Neural Networks might be applicable to this problem as well. Thus, the aspect of sensor fusion will be left for future work.

VII. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A. CONCLUSIONS

The research issues addressed by this thesis were

- Implement the hardware and software for an Inertial Measurement Unit
- Implement the software for a shaft encoder system
- Evaluate the performance for both sensors
- Sensor Fusion

Both the IMU and the shaft encoder systems have been implemented in software and hardware. The sampling frequency for the A/D-Board was set to be 5 kHz. Both systems have been tested with three different linear motion profiles.

The work conducted in addressing the first of these topics revealed several sources of navigation inaccuracy. The A/D Converter board currently in use does not match the IMU's output range for accelerations below about 1 m/sec^2. In addition, due to the vehicle's sophisticated wheel suspension, the IMU's attitude control could not be related to the attitude of the vehicle and was changing with time as the vehicle moved. This introduced a slowly varying and yet significant error in numerically integrating the acceleration.

The second issue addressed proved to be less difficult. Decent results have been obtained for th elinear motion under the condition that no slip occurs and the vehicle's position can be determined to within 0.5 percent accuracy.

The overall motion control system seems to be stable at all. However, it has been observed that computation power for the 68040 processor is scarce. This is mainly to the fact that a public domain GCC Compiler is in use for generating the executable code. This compiler does not seem to generate optimal executable code. In addition, the lack of a math processor and math library functions required that semi-optimal trigonometric functions be implemented in the source code as well, introducing further inaccuracies.

B. RECOMMENDATIONS FOR FUTURE WORK

There are many issues that were briefly addressed in this thesis but could not be investigated in detail. Much work needs to be done in the following areas.

1. Determine the optimal resolution for the A/D-Board based on the anticipated motion profiles.

2. Investigate whether or not variable gain control for the IMU data would improve the performance of the IMU.

3. Develop a scheme for attitude control vice changing the vehicle's suspension.

4. Implement the filter algorithms as determined in this thesis. Care needs to be taken that computation time is crucial and efficient computation methods be used.

5. Implement an Input/Output Kernel utilizing the 68030 processor for online debugging, display of status information, and eventually off-loading of some of the lower priority task such as transferring data between boards.

6. Investigate how the system presented in this thesis would work for most general type of motion including rotational motion and motion in three dimensions.

APPENDIX A: CONSTANTS

Table 1.1: Constants used throughout the text

Universal constant of gravitation	$G = 6.672 \cdot 10^{-11} \; \frac{m^3}{kg \; sec^2}$
Mass of Earth	$M = 5.98 \cdot 10^{24} \; kg$
mean Earth radius	$R_e = 6.371 \cdot 10^6 \; m$

APPENDIX B: MATLAB M-FILES

This appendix contains essential MATLAB M-Files that are being referenced in the text.

1.   IMU.M

The MATLAAB file 'imu.m' is used to analyze the data recorded from the IMU. It makes use of the MATLAB functions 'filter1', 'euler1.m' and 'integral' which are listed following this section.

```
 1  function imu(fname,G,T,f)
 2
 3  % ------------------------------------------------------------------
 4  % function imu(fname,G,T,f)
 5  % ------------------------------------------------------------------
 6  %
 7  % M-File to obtain reliable position data. Procedure:
 8  %
 9  %    1. load data and scale data
10  %    2. plot data in frame {B}
11  %    3. filter data with butterworth LP filter in frame {B}
12  %    4. determine Euler angles and transform data fto frame {R}
13  %    5. integrate data to obtain velocity
14  %
15  % Author:      Thorsten Leonardy
16  % Date:        10/23/97
17  % Compiler:    MATLAB V4.21c
18  %
19  % Input:       fname = name of data file
20  %              G     = gain sequence for channels, default [1 1 1 4]
21  %                      note that G(3) includes the orientation of the
22  %                      IMU's z-axis (>0 is up, <0 is down)
23  %              T     = sampling time for data
24  %              f     = switch for filtering ax data
25  % ------------------------------------------------------------------
26
27  g=9.81;                % local gravitational constant [g=9.81m/s^2]
28
29  if nargin<2
30     G=[1 1 1 4];        % sample gain
31     T=0.01;             % samples per block and channel
32     f=0;                % do not filter data
33  end
34
35  up = G(3)/abs(G(3))    % determine if IMU's z-axis points up
36  G(3)=abs(G(3));
37
38  % load data, ax,ay and az are in [m/sec^2] or [g], wz is in [rad/sec]
39  [t,ax,ay,az,wz]=getdata(fname,G,T);
40
41  disp('>>> Plot data in {B} ...')
42  plotdata(t,ax,ay,az,wz);                  % plot data
43
44  disp('>>> Transform {B} --> {R} ...')
45  [ax,ay,az]=euler1(ax,ay,az,up);           % transform data to reference frame {A}
46
47  disp('>>> Plot data in {R} ...')
48  plotdata(t,ax,ay,az,wz);                  % plot data in {R}
49
50  disp('>>> Integrate data in {R} to obtain v ...')
51  [tv,vx]=integral(t,g*ax,1);               % integrate step by step
52  [tv,vy]=integral(t,g*ay,1);               % integrate step by step
53  [tv,vz]=integral(t,g*(az-up),1);          % integrate step by step
```

```
54
55  figure
56  myplot(tv,vx,'Velocity in frame {R}','','v_x [m/sec]',[3 1 1])
57  myplot(tv,vy,'','','v_y [m/sec]',[3 1 2])
58  myplot(tv,vz,'','t [sec]','v_z [m/sec]',[3 1 3])
59
60  disp('>>> Integrate data in {R} to obtain position ...')
61  [tp,x]=integral(tv,vx,1);              % integrate step by step
62  [tp,y]=integral(tv,vy,1);              % integrate step by step
63  [tp,z]=integral(tv,vz,1);              % integrate step by step
64
65  figure
66  myplot(tp,x,'Position in frame {R}','','x [m]',[3 1 1])
67  myplot(tp,y,'','','y [m]',[3 1 2])
68  myplot(tp,z,'','t [sec]','z [m]',[3 1 3])
69
70  % ------------------------------------------------
71  % filter the data for acceleration in x direction
72  % ------------------------------------------------
73  if f
74    mx=mean(ax);                        % compute the mean
75    my=mean(ay);                        % compute the mean
76    mz=mean(az);                        % compute the mean
77
78
79    % compute the FFT
80    [AX,f]=filter1(ax,6,t(2)-t(1));
81
82    mAX=AX(1);                          % obtain the mean
83    AX(1)=0;                            % suppress dc component
84
85    figure
86    myplot(t,ax,['Acceleration ax in frame {R}, mean is ' num2str(mx)],'t [sec]','ax [g]',[3 1 1])
87
88    myplot(f,AX,['FFT for ax [g], mean is AX(f=0)= ' num2str(mAX) ' [g], fs=5000 Hz'],...
89               'f [Hz]','AX [g]',[3 1 2])
90
91    % zoom on in for f=0..50 Hz
92    ix=find(f<=50);
93    myplot(f(ix),AX(ix),'Blow up view for FFT for ax [g]',...
94               'f [Hz]','AX [g]',[3 1 3])
95
96    % ----------------------------------------------------
97    % filter the data
98    % ----------------------------------------------------
99    af=filter1(ax,10,20/2500,50/2500,0.1,80);  % Cauer filter
100
101   figure
102   myplot(t,af,'Acceleration ax in frame {R} after elliptic filtering',...
103              't [sec]','ax [g]',[2 1 1])
104
105
106
107   % ----------------------------------------------------
108   % Integrate ax
109   % ----------------------------------------------------
110   [t,v]=integral(t,af,6);
111
112   myplot(t,v,'Velocity vx in frame {R} after elliptic filtering',...
113              't [sec]','vx [m/s]',[2 1 2])
114
115 end % of if f
116
117 disp('>>> Plot all figures to disk in postscript format as ''fname_xxx.ps''')
118 for i=1:gcf
119   figure(i)
120   eval(['print -dps2 ' fname '_' num2str(i) '.ps'])
121 end
122
123 return
124 % ----------------------------------------------------------------
125 % end of 'imu.m'
126 % ----------------------------------------------------------------
```

2. FILTER1.M

The file 'filter1' provides a set of suitable filter routines such as an FFT, Chebychev or Butterworth filter, and more.

```
1  function [y,f]=filter1(x,type,a,b,c,d)
2  % ------------------------------------------------------------------
3  % function [y,f]=filter1(x,type,a,b,c,d)
4  % ------------------------------------------------------------------
5  % Author:     Thorsten Leonardy
6  % Date:       10/16/97
7  % Compiler:   MATLAB V4.2c1
8  %
9  % Input:      x = input data matrix (M*N)
10 %             type = utility function (filter) to apply
11 %             a..d = parameter used for some filter types
12 %
13 % type 2..4 average across the rows:
14 %             type = 2 simple mean
15 %             type = 3 average using Simpson's 3/8 rule
16 %             type = 4 average using Simpson's 1/3 rule on 9 samples
17 %             type = 5 average using trapezoidal rule
18 % type 6 operate on each row:
19 %             type =  6 obtain Fourier transform (a is the sample interval in [sec])
20 % type 7 ... 9 operate on first row only:
21 %             type =  7 moving average FIR-Filter         [n Taps]
22 %             type =  8 Butterworth filter              [wp,ws,Rp,Rs]
23 %             type =  9 Chebychev Filter               [wp,ws,Rp,Rs]
24 %             type = 10 Elliptic (Cauer Filter)         [wp,ws,Rp,Rs]
25 %
26 % Output:     y = output data (M*N2/2),
27 %                 N2 is a power of two closest to and less or equal to N
28 %             f = frequency scale (1*N2/2) for y if type=10
29 % ------------------------------------------------------------------
30
31 disp(['*** Function "filter1", type ' num2str(type) ' ***'])
32
33 if type==0
34    y=x;
35    return
36 end
37
38 % compute mean of the sampled data from the channel
39 if type==1
40   y=x(a,:);
41 end
42
43 if type==2
44   y=mean(x);
45 end
46
47 if type==3
48   c=(3/8)*[1 3 3 2 3 3 2 3 3 1];
49   y=c*x/9;
50 end
51
52 if type==4
53   c=(1/3)*[1 4 2 4 2 4 2 4 1];
54   y=c*x(1:9,:)/8;
55 end
56
57 if type==5
58   c=(1/2)*[1 2 2 2 2 2 2 2 2 1];
59   y=c*x/9;
60 end
61
62 % ------------------------------------------------------------------
63 % Fourier Transform of x
64 % ------------------------------------------------------------------
65
66 if type==6
67
68    T=a;                          % sampling time of data
```

```
69    F=1/T;                              % sampling frequency [Hz] of signal
70    m=mean(x');                         % mean of data sequence
71
72    N=size(x,2);                        % total length of data
73    N2=2^(floor(log(N)/log(2)))         % reduced length to power of two
74    x(:,N2+1:N)=[];                     % cut off the data sequence
75    t=T*(0:N2-1);                       % time base corresponding to data
76    f=linspace(0,F,N2);                 % frequency base
77
78    % Matlab computes the Fourier transform of a signal that is sampled
79    % at a sampling frequency fs. The corresponding frequency scale is
80    % expressed in terms of the digital frequency omega=2*pi*(f/fs) in
81    % the range 0..2*pi (any discrete FT is periodic in terms of omega
82    % with period 2*pi).
83
84    y=abs(fft(x'))';                    % compute the Fourier Transfor of x(t)
85    f(:,N2/2+1:N2)=[];                  % discard redundant frequency part
86    y(:,N2/2+1:N2)=[];                  % discard redundant upper half of spectrum
87                                        % X(w) relates now to w=[0,pi]
88    y=y/N2;                             % normalize the amplitude
89
90  end
91
92
93  % ************* moving average FIR filter *********************
94  if type==7
95
96     if nargin<3
97        P=5;
98     end
99     M=P;
100    N=size(x,2);
101
102    x=x(1,:);                          % filter only first row
103
104    x=x-[ zeros(1,1+M) x(1:N-1-M)];    % the delay
105    x=x/(1+M);
106
107    y=zeros(1,N);
108    y(1)=x(1);
109
110    for i=2:N
111       y(i)=y(i-1)+x(i);
112    end
113
114 end
115
116
117 % ---------------------------------------------------------------------
118 % IIR Butterworth filter
119 % ---------------------------------------------------------------------
120 if type == 8
121
122    x=x(1,:);                          % filter only first row
123
124    % filter specifications (digital frequencies)
125    % e.g. if fs=2000Hz and passband edge is supposed to be at fp=500 Hz,
126    % parameter wp must be wp=fp/(fs/2)=500/(2000/2)=0.5 !!!
127    wp=a;      % wp is passband edge [0..1] where 1 relates to fp/(fs/2) ...
128    ws=b;      % stopband edge ...
129    Rp=c;      % ... and max. attenuation [dB] at passband edge
130    Rs=d;      % ... and min. attenuation [dB] at stopband edge
131    [N,wc]=buttord(wp,ws,Rp,Rs);   % filter order and 3dB cutoff-frequency
132    disp(['Butterworth filter order ' num2str(N)])
133
134    %filter process
135    [b,a]=butter(N,wc);                % compute the filter coefficients
136    y=filter(b,a,x);                   % filter the data
137
138 end
139
140 % ----------------------------------------------------------
141 % Chebychev Type II filter
142 % ----------------------------------------------------------
143 if type==9
144
```

```
145     x=x(1,:);                        % filter only first row
146
147     % filter specifications (digital frequencies)
148     % e.g. if fs=2000Hz and passband edge is supposed to be at fp=500 Hz,
149     % parameter wp must be wp=fp/(fs/2)=500/(2000/2)=0.5 !!!
150     wp=a;         % wp is passband edge [0..1] where 1 relates to fp/(fs/2) ...
151     ws=b;         % stopband edge ...
152     Rp=c;         % ... and max. attenuation [dB] at passband edge
153     Rs=d;         % ... and min. attenuation [dB] at stopband edge
154
155     [N,wn]=cheb2ord(wp,ws,Rp,Rs);    % filter order and 3dB cutoff-frequency
156     disp(['Chebychev Type II filter order ' num2str(N)])
157
158     [b,a]=cheby2(N,Rs,wn);              % compute the filter coefficients
159     y=filter(b,a,x);                   % filter the data
160
161 end
162
163 % ----------------------------------------------------
164 % Elliptic filter (Cauer filter)
165 % ----------------------------------------------------
166 if type==10
167
168     x=x(1,:);                        % filter only first row
169
170     % filter specifications (digital frequencies)
171     % e.g. if fs=2000Hz and passband edge is supposed to be at fp=500 Hz,
172     % parameter wp must be wp=fp/(fs/2)=500/(2000/2)=0.5 !!!
173     wp=a;         % wp is passband edge [0..1] where 1 relates to fp/(fs/2) ...
174     ws=b;         % stopband edge ...
175     Rp=c;         % ... and max. attenuation [dB] at passband edge
176     Rs=d;         % ... and min. attenuation [dB] at stopband edge
177
178     [N,Wn]=ellipord(wp,ws,Rp,Rs);    % filter order and 3dB cutoff-frequency
179     disp(['Elliptic filter order ' num2str(N)])
180
181     [b,a]=ellip(N,Rp,Rs,Wn);              % compute the filter coefficients
182     y=filter(b,a,x);                   % filter the data
183
184 end
185
186
187 return
188
189 % --------------------------------------------------------------------
190 % end of 'filter1.m'
191 % --------------------------------------------------------------------
```

3.   EULER1.M

The function 'euler1.m' is used to convert the recorded IMU data which is given in the
sensor frame {S} to the reference frame {R} by means of rotation matrices.

```
 1  function [ax,ay,az]=euler1(ax,ay,az,up)
 2
 3  % --------------------------------------------------------------------
 4  % function [ax,ay,az]=euler1(ax,ay,az,up)
 5  % --------------------------------------------------------------------
 6  %
 7  % M-File for computing the Euler angles for a given set of data
 8  % measured in the sensor frame {S} and transforming the data into
 9  % the reference frame {R}.
10  %
11  % Author:     Thorsten Leonardy
12  % Date:       10/16/97
13  % Compiler:   MATLAB V4.21c
14  %
15  % Input:      ax(1,N) =  acceleration [g] in {S} ax-direction
16  %             ay(1,N) =  acceleration [g] in {S} ay-direction
```

63

```
17  %              az(1,N) =  acceleration [g] in {S} az-direction
18  %              up      =  orientation of sensors z-axis (+1=up,-1=down)
19  %
20  % Return:      acceleration relative to frame {R}
21  % -----------------------------------------------------------------
22
23  % put data into one measurement matrix aS(3,N) relative to Frame {S}
24  aS=[ax;ay;az];
25
26  % ------------------------------------------------
27  % determine the Euler angles based on the average
28  % acceleration during 2nd second
29  % ------------------------------------------------
30  ix=101:200;  ·        % may change this
31  m=mean(aS(:,ix)');    % take the mean of first ix values
32  g=sqrt(m*m');         % the gravity based on the mean
33  disp(['--> mean of g in frame {S} is ' num2str(g,6) ' g'])
34
35  psi=0.0;                       % psi, arbitrary value
36  phi=-asin(m(1));               % phi
37  theta=asin(m(2)/cos(phi));     % theta
38
39  phi=up*phi;
40  theta=up*theta;
41
42  disp(['--> Theta (roll) is ' num2str(theta*180/pi,7) ' degrees'])
43  disp(['--> Phi (pitch) is ' num2str(phi*180/pi,7) ' degrees'])
44  disp(['--> Psi (yaw) is ' num2str(psi*180/pi,7) ' degrees'])
45
46  % ------------------------------------------------
47  % compute elements of the rotation matrix
48  % complete rotation matrix would be R=RZ*RY*RX
49  % ------------------------------------------------
50
51  RX=[   1           0             0        ;      % rotation matrix about X_A
52         0       cos(theta)  -sin(theta) ;
53         0       sin(theta)   cos(theta) ];
54
55  RY=[ cos(phi)      0          sin(phi)    ;      % rotation matrix about Y_A
56        0            1            0         ;
57     -sin(phi)       0          cos(phi)    ];
58
59  RZ=[ cos(psi) -sin(psi)        0          ;      % rotation matrix about Z_A
60       sin(psi)  cos(psi)        0          ;
61         0         0             1          ];
62
63  % ------------------------------------------------
64  % rotate the data successively to frame {A}
65  % ------------------------------------------------
66  aR=RX*aS;        % rotate {B} about {R} x-axis
67  aR=RY*aR;        % rotate new {B} about {R} y-axis
68  aR=RZ*aR;        % rotate new {B} about {R} z-axis
69
70  m=mean(aR(:,ix)');  % take the mean of first ix values
71  g=sqrt(m*m');       % the gravity based on the mean
72  disp(['--> mean of g in frame {A} is ' num2str(g,6) ' g'])
73
74  ax=aR(1,:);
75  ay=aR(2,:);
76  az=aR(3,:);
77
78  return
79  % -----------------------------------------------------------------
80  % end of 'euler1.m'
81  % -----------------------------------------------------------------
```

4.   INTEGRAL.M

This function implements the Newton-Cotes integration formulas as described in the text.

This provides an easy means to compare the results for different integration schemes.

```
 1  function [t,y]=integral(t,x,n)
 2
 3  % ------------------------------------------------------------------
 4  % function [t,y]=integral(t,x,n)
 5  %
 6  % Integrates the input x based on the Newton-Cotes algorithm.
 7  % The integral is computed on each column.
 8  %
 9  % n = the number of panels (n panels require n+1 data points)
10  % t is the time base corresponding to the data.
11  % ------------------------------------------------------------------
12
13  [N,c]=size(t)
14
15  if (c>N)
16      x=x'; t=t'; N=c;    % need data as a vector, N=length of data
17  end
18
19  % prepare the coefficients in the sum formula
20  if (n==1),c=[1 1]/2; end
21  if (n==2),c=[1 2 1]/6; end
22  if (n==3),c=[1 3 3 1]/8; end
23  if (n==4),c=[7 32 12 32 7]/90; end
24  if (n==5),c=[19 75 50 50 75 19]/288; end
25  if (n==6),c=[41 216 27 272 27 216 41]/840; end
26  c=n*(t(2)-t(1))*c;
27
28  for i=1:n:N-n
29      x(i,:)=c*x(i:i+n,:);         % store result in place
30  end
31
32  y=cumsum(x(1:n:N-n,:));
33  t=t(n+1:n:N);               % return the time scale
34
35  return
36  % -----------------------------
37  % End of 'integral.m'
38  % -----------------------------
```

5.   SHAFT.M

In order to analyze the shaft encoder data that was recorded during the different motion
programs.

```
 1  function shaft(fname)
 2
 3  % ------------------------------------------------------------------
 4  % function shaft(fname)
 5  % ------------------------------------------------------------------
 6  %
 7  % M-File to analyze the shaft encoder readings recorded for SHEPHERD's
 8  % motion according to the different motion profiles.
 9  %
10  % Author:      Thorsten Leonardy
11  % Date:        11/11/97
12  % Compiler:    MATLAB V4.21c
13  %
14  % Input:       fname = name of data file (no extension '*.dat')
15  %              e.g. at the prompt >>shaft('linear4')
16  % ------------------------------------------------------------------
17
18  % load data
```

```
19  eval(['load -ascii ' fname '.dat, data=' fname ';' fname '=[];'])
20
21  % reshape the data
22  N=length(data)/8                % number of 10ms intervals contained in data
23  data=reshape(data,8,N);
24  t=0.01*(1:N);                   % the time base
25
26  driveDelta=data(1:2:8,:)';     % driving data [counts/10ms]
27  steerDelta=data(2:2:8,:)';     % steering data [counts/10ms]
28
29  % account for the fact that drive encoders for wheels 2 and 4 read negative
30  % differences if wheels are driving forward
31  driveDelta(:,2:2:4)=-driveDelta(:,2:2:4);
32
33  % accumulate the data to obtain true rotation of motors
34  drive=cumsum(driveDelta);      % the distance travelled
35  steer=cumsum(steerDelta);      % the angle steered
36
37  % scale to SI units
38  drive=drive/87914;    % drive distance in [m]
39  steer=steer/256;      % angle steered in degrees
40
41  % plot data
42  figure
43  for i=1:4
44      if (mod(i,2))
45          subplot(2,2,i+1)
46      else
47          subplot(2,2,i-1)
48      end
49      plot(t,drive(:,i)),grid
50      title(['Wheel ' num2str(i)],'FontSize',8)
51      xlabel('Time [sec]','FontSize',8)
52      ylabel('Drive distance [m]','FontSize',8)
53      set(gca,'FontSize',6,'Box','off')
54      a=axis; a(3)=min(drive(:,i)); a(4)=max(drive(:,i)); axis(a)
55  end
56  eval(['print -dps2 shaft' num2str(gcf) '.ps'])
57
58  figure
59  plot(t,steer),grid
60  title('Steer values for Wheels 1..4 with steer value set to zero','FontSize',8)
61  xlabel('Time [sec]','FontSize',8)
62  ylabel('Steer angle [degrees]','FontSize',8)
63  set(gca,'FontSize',6,'Box','off')
64  ix=min(find(t>=65));
65  for i=1:4
66      text(t(ix),steer(ix,i),['Wheel' num2str(i)],...
67          'HorizontalAlign','left','VerticalAlign','top','FontSize',6)
68  end
69  eval(['print -dps2 shaft' num2str(gcf) '.ps'])
70
71
72  return
73  % ------------------------------------------------------------------
74  % end of 'shaft.m'
75  % ------------------------------------------------------------------
```

APPENDIX C: GCC COMPILER SOURCE-FILES

This appendix lists the C-source code that is being referred to throughout the text. Each individual source file was written in C and crosscompiled using the GCC Compiler Version 2.72 with the following command line:

```
gcc -c -m68040 -o filename.o filename.c
```

1.   IMU.C

The file 'imu.c' provides all the routines required to implement the inertial measurement sensor as outlined in Chapter V. Moreover, they provide the interface for further development of the system.

```
 1  /* ------------------------------------------------------------------- *
 2   *                                                                     *
 3   * File:         I M U . C                                             *
 4   *                                                                     *
 5   * Environment:  GCC Compiler v2.7.2                                   *
 6   * Last update:  10 September 1997                                     *
 7   * Name:         Thorsten Leonardy                                    *
 8   * Purpose:      Provides routines required for controlling the inertial *
 9   *               measurement sensor.                                   *
10   *                                                                     *
11   * Compiled:     >gcc -c -m68040 -o navigat.o navigat.c                *
12   *                                                                     *
13   * ------------------------------------------------------------------- */
14
15  /* --------------------------- R E A D M E -----------------------------
16
17      Here is how the routines work:
18
19      1. Make sure that initVME9325 is called inside main()
20         this will setup the proper interrupt handling for reading data
21         from the accelerometer.
22
23      2. A/D-Block conversions as specified in initVME9325 will be initiated with every
24         10ms timer interrupt. However, to make the data available, make sure that
25         interrupt for conversion complete are being issued:
26
27      3. Call startVME9325 to enable block conversion complete interrupts
28         on IRQ-5 to 68040 processor and therefore copy data into main memory
29
30      4. To seize copying data into main memory, call stopVME9325
31
32      5. The A/D converter is setup such that after every 10ms timer interrupt
33         a block conversion will be initiated. A total of AD_NUM_CONVERSIONS
34         conversions will be performed on the four channels on the IMU
35         in the sequence CH0, CH1, CH2, CH3, CH0, ...
36         The sample time is set to be 25us (hence, one specific channel will
37         be sampled every 100us)
38
39      6. If interrupts are enabled, the most recent data obtained with every
40         10ms timer interrupt will be stored in the structure imu as defined
41         in SHEPHERD.H
```

```
 42
 43        7. The boards status can be observed at the front panel:
 44            (a) green LED is on  -> board performs A/D-Conversions, interrupts enabled
 45            (b) green LED is off -> board performs A/D-Conversions, interrupts disabled
 46            (c) red LED is toggling -> Interrupts are being handled by the handler,
 47                                        data is read from board into SHEPHERD main memory
 48            (d) red LED is on/off  -> interrupt handler is not being called
 49
 50        ------------------------------------------------------------------------ */
 51
 52   #include "shepherd.h"
 53   #include "imu.h"
 54
 55        -
 56   int   adCounter;           /* counter for debugging purposes */
 57   int   mainMemCounter;      /* to count the data stored in main memory */
 58
 59
 60   /* the next is used as temporary storage for analyzing acceleration DATA */
 61   unsigned short *mainMemData;
 62
 63
 64   /* -------------------------------------------------------------------------- *
 65    * initVME9325(void)                                                          *
 66    *                                                                            *
 67    * Environment:  GCC Compiler v2.7.2                                          *
 68    * Last update:  24 July 1997                                                 *
 69    * Name:         Thorsten Leonardy                                            *
 70    *                                                                            *
 71    * Purpose:      Initializes AD-Board VME9325. Board will convert             *
 72    *               analog data from channels specified and store the respec-    *
 73    *               tive digital data (2 Bytes per channel, 12 bit data, lowest  *
 74    *               nibble is zero) sequentially in dual port ram.               *
 75    *                                                                            *
 76    *               Board will operate in Block mode with interrupts and timed   *
 77    *               periodic triggering (10ms cycle). E.g. perform 10 conver-    *
 78    *               sions on each of the four channels. Once 40 conversions are  *
 79    *               made, initiate interrupt to read data into main memory and   *
 80    *               eventually smooth/filter data.                               *
 81    *                                                                            *
 82    * -------------------------------------------------------------------------- */
 83   void initVME9325(void)
 84   {
 85
 86       unsigned char *ad = (unsigned char*) VME9325_BASE;        /* base address */
 87       unsigned char *vmeICR4 = (unsigned char*)VIC_IRQ4;        /* VME ICR IRQ-4*/
 88       long *vadr;                                   /* for Vector base address */
 89
 90       *(ad+0x81)=0x10;    /* software reset */
 91       *(ad+0x81)=0x02;    /* turn both  LEDs on to indicate board undergoes    */
 92                           /* initialization                                   */
 93
 94       /* ---------------------------------------------------------------- *
 95        * Interrupt settings for VIC                                       *
 96        * ---------------------------------------------------------------- */
 97       vadr=(long*)0xffe40158;   /* VBA address for interrupt handler (4 * 0x56 = 0x158) */
 98       *vadr=(long)handlerVME9325;   /* write address of handler into Vector Table */
 99
100       /* set up VIC interface for VME-Bus interrupts to TUARUS. AD-Board asserts   */
101       /* IRQ-4 upon interrupt to VME-Bus. Route as IRQ-2 to MC68040. CAUTION !!!   */
102       /* make sure jumper J7 on AD-Board is set correctly !!!                      */
103       *vmeICR4=0x82; /* disable VME-Bus IRQ4 input, route as IRQ-2 to Processor */
104
105       *(ad+0x83)=0x56;    /* interrupt vector number provided by board to VIC */
106
107       /* program scan sequence (may wish to arrange channels to be scanned differently) */
108       /* channels are scanned, converted and stored in memory in this order         */
109       /*    *(ad+0x87)=0x00;    /* channel 0 (ax, +-7.5V input range, gain x1) */
110       /*    *(ad+0x87)=0x01;    /* channel 1 (ay, +-7.5V input range, gain x1) */
111       *(ad+0x87)=0x60;     /* channel 0 (ax, +-7.5V input range, gain x8) */
112       *(ad+0x87)=0x61;     /* channel 1 (ay, +-7.5V input range, gain x8) */
113       *(ad+0x87)=0x02;     /* channel 2 (az, +-7.5V input range, gain x1) */
114       *(ad+0x87)=0xc3;     /* channel 3 (wy, +-2.5V input range, gain x4) */
115                            /* gain x4 to cover max. input range +-10V,    */
116                            /* set EOS bit to indicate end of scan sequence*/
117
```

```
118      /* setup Board Control Register */
119      *(ad+0x85)=0x08;    /* enable timer circuit, enable interrupts              */
120                          /* block mode, software initiates very first trigger    */
121
122      /* setup timed periodic triggering circuit for 50usec ( T = 10 * 10 / 2 MHz )*/
123      *(ad+0x8f)=0x54;    /* setup counter to receive single byte prescaler count */
124      *(ad+0x8b)=0x0A;    /* load prescaler value into Timer Prescaler Register    */
125      *(ad+0x8f)=0x94;    /* setup counter to receive single byte timer count      */
126      *(ad+0x8d)=0x0A;    /* load Conversion Timer Register                        */
127
128      /* load conversion count register */
129      *((unsigned short *)(ad+0x90))=200;
130
131      /* initialization is complete */
132      *(ad+0x81)=0x01;    /* turn off both LED, disable interrupts                 */
133
134      sioOut(0,"A/D-Board initialized\n\r");
135
136      return;
137  }    /* end of AD_Init */
138
139
140  /* ----------------------------------------------------------------------------- *
141   * analyzeVME9325                                                                *
142   *                                                                               *
143   * Environment:  GCC Compiler v2.7.2                                             *
144   * Last update:  24 July 1997                                                    *
145   * Name:         Thorsten Leonardy                                               *
146   *                                                                               *
147   * Purpose:      Saves the data for one complete block conversion cycle from     *
148   *               dual-port RAM of A/D-Board to Shepherd's main memory.           *
149   *               In the future, this routine shall be utilized to analyze        *
150   *               and filter the data and save only the filtered data.            *
151   *               This is called from the interrupt handler routine               *
152   *               AD_Handler.                                                     *
153   *                                                                               *
154   * ----------------------------------------------------------------------------- */
155  void analyzeVME9325(void)
156  {
157      unsigned short *ad;  /* base address for data */
158      int i;
159      unsigned short adData[AD_NUM_CONVERSIONS];
160
161
162      ad=(unsigned short*)VME9325_DATA;  /* load base address for dual port RAM */
163
164      /* ------------------------------------------------------- *
165       * here goes the filtering ...                             *
166       * ------------------------------------------------------- */
167      if ((adCounter%5)==0)
168          toggleVME((unsigned char *)0xfd800000,0x01); /* toggle red LED every 50 msec*/
169
170      adCounter++;
171
172      /* ------------------------------------------------------- *
173       * This is temporary backup                               *
174       * ------------------------------------------------------- */
175
176      for (i=0; i<AD_NUM_CONVERSIONS; i++) {
177          adData[i]=*ad++;                /* neglect lower nibble */
178          *mainMemData++=adData[i];       /* save data in main memory */
179      }
180
181  #ifdef 0
182
183      /* once data is filtered, store obtained values in imu */
184      imu.ax=adData[0];
185      imu.ay=adData[1];
186      imu.az=adData[2];
187      imu.omega_z=adData[3];
188
189  #endif
190
191      /* reload start conversion register for next block conversion */
192      ad=(unsigned short*)0xfd800090; /* address for SCR */
193      *ad=AD_NUM_CONVERSIONS;          /* reload register */
```

```c
194
195      return;
196  }    /* end of analyzeVME9325 */
197
198
199  /* --------------------------------------------------------------------------- *
200   * startVME9325(void)                                                           *
201   *                                                                             *
202   * Environment:   GCC Compiler v2.7.2                                          *
203   * Last update:   10 September 1997                                            *
204   * Name:          Thorsten Leonardy                                           *
205   *                                                                             *
206   * Purpose:       enables interrupts issued by the VME9325 board.             *
207   *                                                                             *
208   * Called from:   whatever function.                                          *
209   *                                                                             *
210   * --------------------------------------------------------------------------- */
211  void startVME9325(void)
212  {
213      unsigned char *statusRegister=(unsigned char *)VME9325_BASE+0x0081;
214      unsigned char *vmeICR4 = (unsigned char*)VIC_IRQ4;          /* VME ICR IRQ-4*/
215
216      /* initialize global variables ... */
217       mainMemData=(unsigned short *)IMU_DATA_ADR;  /* start address for data storage */
218       adCounter=0;                                 /* counter for debugging purposes */
219
220      *vmeICR4=0x02;  /* enable VME-Bus IRQ4 input, route as IRQ-2 to Processor      */
221
222      /* write status register to enable interrupt and turn off red LED             */
223      *statusRegister=0x09;    /* turn off both LEDs, enable interrupts             */
224
225
226      return;
227  }    /* end of startVME9325 */
228
229
230  /* --------------------------------------------------------------------------- *
231   * stopVME9325(void)                                                            *
232   *                                                                             *
233   * Environment:   GCC Compiler v2.7.2                                          *
234   * Last update:   10 September 1997                                            *
235   * Name:          Thorsten Leonardy                                           *
236   *                                                                             *
237   * Purpose:       disables interrupts off the VME9325 AD-Board. Yet, board     *
238   *                will still perform A/D-Conversions but data will not be       *
239   *                made available to the operating system.                      *
240   * Called from:                                                                *
241   *                                                                             *
242   * --------------------------------------------------------------------------- */
243  void stopVME9325(void)
244  {
245      unsigned char *statusRegister=(unsigned char *)VME9325_BASE+0x0081;
246      unsigned char *vmeICR4 = (unsigned char*)VIC_IRQ4;   /* VME ICR IRQ-4*/
247
248  #ifdef 0
249      /* initialize global variables ... */
250       mainMemData=(unsigned short *)IMU_DATA_ADR;  /* start address for data storage */
251       adCounter=0;                                 /* counter for debugging purposes */
252  #endif
253
254      *vmeICR4=0x82;  /* disable VME-Bus IRQ4 input, route as IRQ-2 to Processor */
255
256      /* write status register to disable interrupt and turn off red LED */
257      *statusRegister=0x01;    /* turn off both LEDs, disable interrupts  */
258
259      return;
260  }    /* end of stopVME9325 */
261
262
263
264  /****************************************************************************
265     Assembler routines
266  ****************************************************************************/
267
268
269
```

```
270
271  /* ------------------------------------------------------------------------ *
272   * handlerVME9325                                                           *
273   *                   .                                                      *
274   * Environment:  GCC Compiler v2.7.2                                        *
275   * Last update:  10 September 1997                                          *
276   * Name:         Thorsten Leonardy                                          *
277   *                                                                          *
278   * Purpose:      Handles the VME-Bus interrupt request from the A/D-Board.  *
279   *                                                                          *
280   * ------------------------------------------------------------------------ */
281
282
283      asm("
284          .even
285          .text
286          .globl _handlerVME9325
287
288  _handlerVME9325:
289
290
291          link    a6,#-184            /* allocate 184 Bytes on stack to save registers   */
292          fsave   a6@(-184)
293  #ifdef 0
294          fmovemx fp0-fp7,sp@-        /* move floating point registers 80 bit each       */
295          fmovel  fpcr,sp@-           /* move floating point Control Regioster           */
296          fmovel  fpsr,sp@-           /* move floating point status register             */
297          fmovel  fpiar,sp@-          /* move floating point Instruction address register */
298  #endif
299          moveml  d0-d7/a0-a5,sp@-    /* save data and address registers (14*4 Byte)     */
300
301          addq.l  #1,_adCounter       /* increment counter (testing purpose only */
302
303          move.l  #0xfd800081,a0      /* load address status register */
304          and.b   #0xfd,(a0)          /* turn off green LED            */
305
306          move.l  #0xfd800090,a0      /* reload start conversion register */
307          move.w  #200,(a0)
308
309
310  #ifdef 1
311
312          move.l  #0xfd820000,a0      /* load address for dual port RAM */
313          lea     _mainMemData,a1
314          move.l  (a1),a2
315
316          clr.l   d0                  /* loop counter */
317
318  _loop:
319          cmp.l   #199,d0
320          ble.b   _proceed
321          nop
322          bra.b   _done
323          nop
324
325  _proceed:
326
327          move.w  (a0),d1             /* read next two byte of dual port RAM
328          nop                         /* caution: need this due to pipelining */
329          move.w  d1,(a2)
330          nop
331          addq.l  #2,a0               /* increment pointer in dual port RAM */
332          addq.l  #2,a2               /* increment pointer to next main memory location */
333          addq.l  #1,d0               /* increment loop counter */
334          bra.b   _loop
335
336  _done:
337
338          move.l  a2,(a1)             /* write back the next main memory location */
339
340
341  /*      jsr     _analyzeVME9325     /* copy data from A/D-Boards dual-port RAM to main  */
342                                      /* memory and filter, analyze it                    */
343  #endif
344
345
```

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```
346          moveml    sp@+,d0-d7/a0-a5
347
348   #ifdef 0
349          fmovel    sp@+,fpiar
350          fmovel    sp@+,fpsr
351          fmovel    sp@+,fpcr
352          fmovemx   sp@+,fp0-fp7
353   #endif
354
355          frestore  a6@(-184)
356          unlk      a6
357
358          rte
359      ");
360
361
362   /*******************************************************************************
363     End of imu.c
364     *****************************************************************************/
365
```

2.   MOTOR.C

The file 'motor.c' provides the routines required to control the servo motors. Although the listing was already given by Mays/Reid [1], some changes had beend done to improve the overall execution time.

```
1    /* =====================================================================
2    // Edward Mays
3    // Shepherd project
4    // 20 February 1997
5    // update: 27 October 1997 Thorsten Leonardy
6    //          -> provide code to detect slip,
7    //          -> eliminate calls to readDriveEncoders, readSteerEncoders
8    //             by including code in readEncoders (improves execution speed)
9    //          -> compute speed and angular velocity immediately inside
10   //             readEncoders.
11   // MotionControl
12   // =====================================================================*/
13
14
15   #include "shepherd.h"
16   #include "motor.h"
17   #include "movement.h"
18   #include "math.h"
19
20   double theta, omega, speed;
21   double a,                     /* acceleration in cm/sec^2 */
22          dd[4];                 /* driveDelta required for velocity to steer */
23   int timeForTurn[8];           /* storage for time it took to rotate 360 degrees [10ms] */
24   short testSpeed=0x0b00;       /* temp variable for changing speed */
25   double radPerDigit[ARRAY_SIZE];
26   int ddc=10000,tc=2000;        /* desired vale for driveDelta */
27
28   int *leoData=(int *)0x00100000; /* start data storage */
29
30
31   void readEncoders() {
32      readDriveEncoders(driveReadings);
33      readSteerEncoders(steerReadings);
34   }
35
36
37   void readDriveEncoders(unsigned long int array[])
38   {
39      unsigned char *p=(unsigned char*)VMECTR1, c1, c2, c3;
40      int ix;
41      long int temp;
```

```
42
43      for (ix=0; ix<4; ix++) {   /* read all four motors subsequentially */
44
45          *(p+3)=0x03;                /* load  output latch from counter */
46          *(p+3)=0x01;                /* control register, initialize two-bit output latch */
47
48          /* read three bytes for specific counter ix and save in status    */
49          /* first access to Output Latch Register reads least significant */
50          /* byte first                                                     */
51
52          c1 = *(p+1) & 0x00ff;
53          c2 = *(p+1) & 0x00ff;
54          c3 = *(p+1) & 0x00ff;
55  --    array[ix] = ((unsigned int)c1)| ((unsigned int)c2 << 8) |
56                  ((unsigned int)c3 << 16);
57
58          p=p+4;                          /* increment pointer for next counter */
59
60
61      }
62      return;
63  } /* end of readDriveEncoders */
64
65
66  void readSteerEncoders(unsigned long int array[])
67  {
68      unsigned char *p=(unsigned char*)(VMECTR1 + 0x0100), c1, c2, c3;
69      int ix;
70
71
72      for (ix=0; ix<4; ix++) {   /* read all four motors subsequentially */
73
74          *(p+3)=0x03;                /* load  output latch from counter */
75          *(p+3)=0x01;                /* control register, initialize two-bit output latch */
76
77
78      /* read three bytes for specific counter ix and save in status */
79      /* first access to Output Latch Register reads least significant byte first */
80
81          c1 = *(p+1) & 0x00ff;
82          c2 = *(p+1) & 0x00ff;
83          c3 = *(p+1) & 0x00ff;
84          array[ix] = ((unsigned int)c1)| ((unsigned int)c2 << 8) |
85                  ((unsigned int)c3 << 16);
86
87
88          p=p+4;                                      /* increment pointer for next counter */
89
90      }
91      return;
92  } /* end of readSteerEncoders */
93
94
95
96  void computeActualRates()
97  {
98
99  int i;
100 double count,speed;
101
102 for(i=0; i<=3; i++)
103    {
104    if(PreviousCountSpeed[i] == 99999999)  /* for derivative for speed  */
105      actualSpeeds[i]= 0.0;
106    else
107      actualSpeeds[i]=
108        (convertDifference((driveReadings[i] - PreviousCountSpeed[i]))
109        *DigitToCmDrive[i])/DELTA_T;
110    PreviousCountSpeed[i] = driveReadings[i];
111
112    if(PreviousCountSteer[i] == 99999999)  /* for derivative for steering  */
113      actualAngleRates[i]= 0.0;
114    else
115      actualAngleRates[i]=
116          (convertDifference((steerReadings[i] - PreviousCountSteer[i]))
117        *digitToRadSteer)/DELTA_T;
```

```
118    PreviousCountSteer[i] =  steerReadings[i];
119       }
120  }
121
122
123
124  void accumulateDriveSpeed()
125  {
126   int i;
127
128  for(i=0;i<=3;i++){
129     Display_Speeds[i] += actualSpeeds[i];
130   }
131   return;
132  }
133
134  void accumulateDriveSteer()
135  {
136   int i;
137
138  for(i=0;i<=3;i++){
139     Display_Steers[i] += 10*actualAngleRates[i];
140     actualAngles[i]   += actualAngleRates[i]*DELTA_T;
141  }
142   return;
143  }
144
145
146
147  /*******************************************************************************
148     Function convertDifference() returns the difference between the new shaft
149     encoder position and the old shaft encoder position. The shaft encoder values
150     contain only 24 bits (0x000000-0xffffff). The routine adjusts for the trans-
151     ition from 0xffffff to 0x000000 and vice versa.
152  *******************************************************************************/
153
154  int convertDifference(int value)
155  {
156     if(value < -0x800000)
157        value &= 0x00ffffff;
158     else  if(value >= 0x800000)
159        value |= 0xff000000;
160
161     return value;
162  }
163
164
165  /* ---------------------------------------------------------------- *
166   * readNewEncoder()                                                 *
167   *                                                                  *
168   * Environment:  GCC Compiler v2.7.2                                *
169   * Name:         Thorsten Leonardy                                  *
170   * Last update:  10/27/97                                           *
171   * Purpose:      This function reads the counter status for drive and steer *
172   *               motors every 10ms and stores the current values in the *
173   *               variables 'driveReadings' and 'steerReadings'. In addition, *
174   *               the incremental change to the last update is stored in the *
175   *               variables 'driveDelta' and 'steerDelta' to allow for compu- *
176   *               ting the most current speeds and angular velocities. *
177   *                                                                  *
178   * Called from:  driver() in movement.c                            *
179   * ---------------------------------------------------------------- */
180  void readNewEncoder()
181  {
182
183     unsigned char *p,*d;
184     int ix;
185
186     p=(unsigned char*)VMECTR1;  /* access steering counter registers        */
187
188     for (ix=0; ix<4; ix++) {      /* read all four driving motors sequentially  */
189
190        driveCountPrevious[ix]=driveCount[ix]; /* save previous value          */
191        steerCountPrevious[ix]=steerCount[ix]; /* save previous value          */
192
193        /* ------------------------------- */
```

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```
194         /* read drive encoders for wheel ix */
195         /* ------------------------------ */
196         *(p+3)=0x03;                         /* load  output latch from counter */
197         *(p+3)=0x01;                         /* initialize two-bit output latch */
198
199         d=((unsigned char*)&driveCount[ix])+2; /* start with LSB, need offset    */
200         *d-- = *(p+1) & 0x00ff;              /* read LSB first                 */
201         *d-- = *(p+1) & 0x00ff;              /* read next byte                 */
202         *d   = *(p+1) & 0x00ff;              /* read most significant byte      */
203
204         /* ------------------------------ */
205         /* read steer encoders for wheel ix */
206         /* ------------------------------ */
207         *(p+0x103)=0x03;                     /* load  output latch from counter */
208         *(p+0x103)=0x01;                     /* initialize two-bit output latch */
209
210         d=((unsigned char*)&steerCount[ix])+2; /* load LSB first                 */
211         *d-- = *(p+0x101) & 0x00ff;          /* read LSB first                 */
212         *d-- = *(p+0x101) & 0x00ff;          /* read next byte                 */
213         *d   = *(p+0x101) & 0x00ff;          /* read most significant byte      */
214
215         p=p+4;                               /* increment pointer for next motor*/
216
217         /* determine difference between previous and current encoder reading */
218         steerDelta[ix]=(steerCount[ix]-steerCountPrevious[ix])/256;
219         driveDelta[ix]=(driveCount[ix]-driveCountPrevious[ix])/256;
220
221         /* consider the fact that a positive driveDelta for wheels 2 and 4 */
222         /* indicate that wheel is driving backwards !!! Thgus, change sign */
223         driveDelta[ix]=(driveCount[ix]-driveCountPrevious[ix])/256;
224
225         /* the following is just for testing purposes [leo, 11/17/97] */
226         *encoderData++=driveDelta[ix];       /* store in main memory */
227         *encoderData++=steerDelta[ix];       /* store in main memory */
228
229     } /* end of for */
230
231     /* account for the fact that a positive driveDelta for wheels 2 and 4 */
232     /* indicate that wheel is driving backwards !!! Thus, change sign to  */
233     /* obtain a positive driveDelta for wheel driving forward !!!         */
234     driveDelta[1]=-driveDelta[1];
235     driveDelta[3]=-driveDelta[3];
236
237     return;
238
239 } /* end of readNewEncoder */
240
241
242
243 /* ------------------------------------------------------------------------ *
244  * readNewEncoder()                                                         *
245  *                                                                          *
246  * Environment:  GCC Compiler v2.7.2                                        *
247  * Name:         Thorsten Leonardy                                          *
248  * Last update:  10/27/97                                                   *
249  * Purpose:      This function reads the counter status for drive and steer *
250  *               motors every 10ms and stores the current values in the    *
251  *               variables 'driveReadings' and 'steerReadings'. In addition, *
252  *               the incremental change to the last update is stored in the *
253  *               variables 'driveDelta' and 'steerDelta' to allow for compu- *
254  *               ting the most current speeds and angular velocities.       *
255  *                                                                          *
256  * Called from:  driver() in movement.c                                     *
257  * ------------------------------------------------------------------------ */
258 void readEncoder()
259 {
260
261     unsigned char *p,*d;
262     int ix;
263
264     p=(unsigned char*)VMECTR1;  /* access steering counter registers         */
265
266     for (ix=0; ix<4; ix++) {     /* read all four driving motors sequentially */
267
268         driveCountPrevious[ix]=driveCount[ix]; /* save previous value          */
269         steerCountPrevious[ix]=steerCount[ix]; /* save previous value          */
```

```
270
271        /* ------------------------------- */
272        /* read drive encoders for wheel ix */
273        /* ------------------------------- */
274        *(p+3)=0x03;                              /* load  output latch from counter */
275        *(p+3)=0x01;                              /* initialize two-bit output latch */
276
277        d=((unsigned char*)&driveCount[ix])+2; /* start with LSB, need offset    */
278        *d-- = *(p+1) & 0x00ff;                   /* read LSB first                 */
279        *d-- = *(p+1) & 0x00ff;                   /* read next byte                 */
280        *d   = *(p+1) & 0x00ff;                   /* read most significant byte     */
281
282        /* ------------------------------- */
283        /* read steer encoders for wheel ix */
284        /* ------------------------------- */
285        *(p+0x103)=0x03;                          /* load  output latch from counter */
286        *(p+0x103)=0x01;                          /* initialize two-bit output latch */
287
288        d=((unsigned char*)&steerCount[ix])+2; /* load LSB first                 */
289        *d-- = *(p+0x101) & 0x00ff;               /* read LSB first                 */
290        *d-- = *(p+0x101) & 0x00ff;               /* read next byte                 */
291        *d   = *(p+0x101) & 0x00ff;               /* read most significant byte     */
292
293        p=p+4;                                    /* increment pointer for next motor*/
294
295        /* determine difference between previous and current encoder reading */
296        steerDelta[ix]=(steerCount[ix]-steerCountPrevious[ix])/256;
297        driveDelta[ix]=(driveCount[ix]-driveCountPrevious[ix])/256;
298
299     } /* end of for */
300
301     /* account for the fact that a positive driveDelta for wheels 2 and 4 */
302     /* indicate that wheel is driving backwards !!! Thus, change sign to  */
303     /* obtain a positive driveDelta for wheel driving forward !!!         */
304     driveDelta[1]=-driveDelta[1];
305     driveDelta[3]=-driveDelta[3];
306
307     return;
308
309  } /* end of readEncoder */
310
311
312
313  /* ---------------------------------------------------------------------- *
314   * computeSpeedAndAngle()                                                 *
315   *                                                                        *
316   * Environment:  GCC Compiler v2.7.2                                      *
317   * Name:         Thorsten Leonardy                                        *
318   * Last update:  11/21/97                                                 *
319   * Purpose:      This function computes the speeds, angles and angular velo- *
320   *               city for all four wheels based on the most recent shaft  *
321   *               encoder readings from readNewEncoder().                  *
322   *                                                                        *
323   * Called from:  driver() in movement.c                                   *
324   * ---------------------------------------------------------------------- */
325  void computeSpeedAndAngle(void)
326  {
327
328     int i;
329
330     /* compute measured driving speed [cm/sec] and steering angle [rad] and */
331     /* steering rate [rad/sec].                                             */
332     for(i=0; i<=3; i++) {
333        actualSpeeds[i]     = ((double)driveDelta[i])*CM_PER_DIGIT/0.01;
334        actualAngles[i]    += ((double)steerDelta[i])*RAD_PER_DIGIT;
335        actualAngleRates[i] = ((double)steerDelta[i])*RAD_PER_DIGIT/0.01;
336     }
337     return;
338  }
339
340
341
342  /*                                                          */
343  /* Verifies validity of incoming speeds/angles and converts */
344  /* digitial input for the DA board                          */
345  /*                                                          */
```

```
346  void driveMotors(){
347
348      int ix,Speed_Digit,Steer_Digit, counter;
349      double speed1, steer1, temp;
350
351      unsigned short bitMask=0x8000;         /* access bit 15 for align  wheel 1 */
352      unsigned short *servoStatus=(unsigned short *)(VME9421+0x00ca); /* digital input */
353
354      bitMask = bitMask >> 3;
355
356      /*  updateWheelDrive();   wheel values for driving                  */
357    . /*  updateWheelSteer();                                .           */
358      /*  comupte the current actual wheel direction in WheelDirAct[] */
359
360      if (mode != 100){
361        for(ix =0; ix <ARRAY_SIZE; ix++){
362          /* ********************steering/driving interaction*************    */
363          /* here +/- 1/50 of the steering value is added to the driving    */
364          /* for each specified wheel. Note the negative sign on elements [1]  */
365          /* and [3]provide the same direction driving as elements [0] and [2] */
366
367          Omega_Speed = desiredSpeeds[ix] +
368           SteerDriveInteract*desiredAngleRates[ix]*18.9; /* cm/sec */
369
370          /* conversion to digits   */
371          Speed_Digit = velocityReferenceTable(Omega_Speed,ix) +
372      DriveFeedBackGain*(Omega_Speed - actualSpeeds[ix]);
373          Steer_Digit = rateReferenceTable(desiredAngleRates[ix])
374    + steerFeedbackGain*(desiredAngleRates[ix]-actualAngleRates[ix])
375    + angleFeedbackGain*norm(desiredAngles[ix]-actualAngles[ix]);
376
377          if (Speed_Digit>DigitsHigh)            /* Limitation  */
378            Speed_Digit= DigitsHigh;
379          if (Steer_Digit>DigitsHigh)
380            Steer_Digit= DigitsHigh;
381          if (Speed_Digit<DigitsLow)
382            Speed_Digit= DigitsLow;
383          if (Steer_Digit<DigitsLow)
384            Steer_Digit= DigitsLow;
385
386          switch(mode){
387    case 2:
388    case 3:
389    case 4:
390    case 5:
391    case 6:
392    case 7:
393    case 8:
394    case 9:
395    case 10:
396          case 11:    /* case 11: linear test drive, added 11/03/97 Leo */
397      speedDigits[ix]= (short)Speed_Digit;  /* casting to short */
398      steerDigits[ix]= (short)Steer_Digit;
399      break;
400
401    case 1:
402      speed1 = speedDigits[ix];
403      steer1 = steerDigits[ix];
404      if ( speed1 > 0) speed1--;
405      if ( speed1 < 0) speed1++;
406      if ( steer1 > 0) steer1--;
407      if ( steer1 < 0) steer1++;
408    . speedDigits[ix] = speed1;
409      steerDigits[ix] = steer1;
410        break;
411          } /* end switch */
412         } /* end for */
413        } /* end if */
414        else {
415          for (ix=0; ix<3; ix++){
416      steerDigits[ix] = 0;
417    }
418    for (ix=0; ix<4; ix++){
419      speedDigits[ix] = 0;
420    }
421
```

```
422     switch(modeTstate){
423       case 0:
424          steerDigits[3] = 50*Flag;
425          modeTstate = 1;
426          break;
427
428       case 1:
429          modeTstate = 2;
430          break;
431
432       case 2:
433          modeTstate = 3;
434          break;
435
436       case 3:
437          modeTstate = 4;
438          break;
439
440       case 4:           - - -
441          modeTstate = 5;
442          break;
443
444       case 5:
445          modeTstate = 6;
446          break;
447
448       case 6:
449          modeTstate = 7;
450          break;
451
452
453       case 7:
454          modeTstate = 8;
455          break;
456
457       case 8:
458          modeTstate = 9;
459          break;
460
461       case 9:
462          modeTstate = 10;
463          break;
464
465       case 10:
466          modeTstate = 11;
467          break;
468
469       case 11:
470          modeTstate = 12;
471          break;
472
473       case 12:
474          modeTstate = 13;
475          break;
476
477       case 13:
478          modeTstate = 14;
479          break;
480
481       case 14:
482          modeTstate = 15;
483          break;
484
485       case 15:
486          modeTstate = 16;
487          break;
488
489       case 16:
490          modeTstate = 17;
491          break;
492
493       case 17:
494          modeTstate = 18;
495          break;
496
497       case 18:
```

```
498          modeTstate = 19;
499          break;
500
501     case 19:
502         if (bitMask&*servoStatus)/* read servo status, */
503   {                       /*wait until wheel aligned */
504             Flag = -Flag;
505             modeTstate = 20;
506   }
507          break;
508
509     case 20:
510          steerDigits[3] = 0;
511          modeTstate = 21;
512          break;
513
514     case 21:
515          modeTstate = 22;
516          break;
517
518     case 22:
519          modeTstate = 23;
520          break;
521
522     case 23:
523          modeTstate = 24;
524          break;
525
526     case 24:
527          modeTstate = 25;
528          break;
529
530     case 25:
531          modeTstate = 26;
532          break;
533
534     case 26:
535          modeTstate = 27;
536          break;
537
538     case 27:
539          modeTstate = 0;
540          break;
541
542     default :   break;
543   } /* end switch */
544         } /* end else */
545
546  #ifdef 0
547      driveSteer(steerDigits);
548      driveSpeeds(speedDigits);
549  #endif
550
551      /* here is a more efficient way of setteing the speeds [Leo, 11/18/97] */
552      /* instead of using the functions driveSteer and driveSpeeds ...       */
553      setServoSpeed();
554
555
556  }/* end driveMotors */
557
558
559
560  double velocityReferenceTable(double desiredVelocity,int i)
561  {
562     double inVelocity,
563            outVelocity;
564
565     inVelocity=new_abs(desiredVelocity);
566
567      if (inVelocity>=0.0 && inVelocity<=5.0)
568        outVelocity = inVelocity*K1[i];
569
570      if (inVelocity>5.0 && inVelocity< 8.0)
571        outVelocity = inVelocity*K2[i];
572
573      if (inVelocity>=8.0 && inVelocity<20.0)
```

79

```c
574        outVelocity = inVelocity*K3[i];
575
576     if (inVelocity>=20.0 && inVelocity<= 70.0)
577        outVelocity = inVelocity*K4[i];
578
579    if (inVelocity>70.0 && inVelocity<K5)
580        outVelocity = inVelocity*K6[i];
581
582      if (inVelocity> K5)
583       outVelocity=1023;
584
585      if (desiredVelocity< 0.0)
586        outVelocity = - outVelocity;
587
588     return outVelocity;
589  } /* end velocityLookupTable */
590
591
592  double rateReferenceTable(double desiredRate)
593  {
594     double inRate,
595            outDigit;
596
597     /*outDigit = new_abs(desiredRate); *//* test only */
598
599      inRate=new_abs(desiredRate);
600
601      if (inRate<= 5.234)
602        outDigit = inRate*195.4155 ;
603      else
604         outDigit=1023;
605
606
607      if (desiredRate< 0.0)
608        outDigit = - outDigit;
609
610     return outDigit;
611  }
612
613
614
615  /* --------------------------------------------------------------------------- *
616   * readOneEncoder()                                                            *
617   *                                                                             *
618   * Environment:  GCC Compiler v2.7.2                                           *
619   * Name:         Thorsten Leonardy                                             *
620   * Last update:  10/27/97                                                      *
621   * Purpose:      Reads only the encoder specified by 'wheel':                  *
622   *               wheel = 0 ... 3 reads drive encoder for wheel 1..4            *
623   *               wheel = 4 ... 7 reads steer encoder for wheel 1..4            *
624   * Note:         !!! The data (24 bit) is still left adjusted !!!              *
625   * --------------------------------------------------------------------------- */
626  void readOneEncoder(int ix, int *data)
627  {
628
629     unsigned char *p,*d;
630
631     p=(unsigned char*)VMECTR1;              /* access steering register       */
632     p=p+4*ix;
633     if (ix>3) p=p+0x0090;      /* account for the fact VMECTR2=VMCTR1+0x100 */
634
635     *(p+3)=0x03;                            /* load  output latch from counter */
636     *(p+3)=0x01;                            /* initialize two-bit output latch */
637
638     d=(unsigned char *)data;               /* start with LSB, need offset    */
639     d=d+2;
640     *d-- = *(p+1) & 0x00ff;       /* read LSB first                    */
641     *d-- = *(p+1) & 0x00ff;       /* read next byte                    */
642     *d  = *(p+1) & 0x00ff;       /* read most significant byte        */
643
644     return;
645
646  } /* end of readOneEncoder */
647
648
649  /* --------------------------------------------------------------------------- *
```

```
650   * linearMotion()                                                              *
651   *                                                                             *
652   * Environment:  GCC Compiler v2.7.2                                           *
653   * Name:         Thorsten Leonardy                                             *
654   * Last update:  10/27/97                                                      *
655   * Purpose:      IMplements a linear motion test profile such that the         *
656   *               vehicle is following steps in successive 10sec time           *
657   *               intervals.                                                    *
658   * Call:         User presses 'l' on the keyboard (see user() in file user.c)*
659   * ------------------------------------------------------------------------- */
660  void linearMotion1(void)
661  {
662      double v1x, v1y, v2, v1yv1xRatio,omega2,omega3, beta,ro,ro2,wheelAngleV;
663      int ix,Speed_Digit,Steer_Digit;
664      short *servoOut;
665
666      /* read all shaft encoders */
667      readNewEncoder();
668
669      /* compute the actual rates, velocities and angles */
670      for (ix=0; ix<4; ix++){
671          driveSpeed[ix]=driveDelta[ix]*CM_PER_DIGIT/DELTA_T;      /* [cm/s] */
672          steerRate[ix]=steerDelta[ix]/DELTA_T;
673          steerAngle[ix]=steerAngle[ix]+steerDelta[ix]*RAD_PER_DIGIT;
674      } /* end of for ... */
675
676
677      /* initialize temporary variables */
678      speed=motion.Speed;
679      theta=motion.Theta;
680      omega=motion.Omega;
681
682      /* ------------------------------------------------------------------------ *
683       * body motion (former in movement.c)                                       *
684       * ------------------------------------------------------------------------ */
685
686      a=2.0;   /* acceleration is 2cm/sec^2 */
687
688      if (time<1000) {
689          speed=a*time/100.0;  /* rise linearly from 0 ..20 cm/sec in 10 secs */
690      }
691
692      if (time==1000){
693          speed=a*10.0;     /* vehicle speed constant for next 10 sec */
694      }
695
696      if (time>=2000)
697          if (time<3000)
698              speed=a*(3000-time)/100.0;    /* decelerate to zero speed for 20sec..30sec */
699
700      if (time==3000){
701          speed=0.0;    /* stop vehicle for 30sec..40sec */
702      }
703
704      if (time>=4000)
705          if (time<5000)
706              speed=a*(4000.0-time)/100.0;   /* reverse motion, move back for 40sec .. 50sec */
707
708      if (time==5000){
709          speed=-a*10.0;    /* move back with constant velocity */
710      }
711
712      if (time>=6000)
713          if (time<7000)
714              speed=a*(time-7000.0)/100.0;
715
716      if (time==7000){
717          mode=0;
718          stopVME9325();    /* stop A/D-Board */
719          allOffAndZero();
720      }
721
722      /* compute required derivatives */
723      speedDot=(speed-motion.Speed)/DELTA_T;
724      thetaDot=(theta-motion.Theta)/DELTA_T;
725      omegaDot=(omega-motion.Omega)/DELTA_T;
```

81

```
726
727         /* update the motion */
728         motion.Speed = speed;
729         motion.Theta = theta;
730         motion.Omega = omega;
731
732         /* update the vehicle configuration */
733         vehicle.heading = vehicle.heading + motion.Omega*DELTA_T;
734         vehicle.coord.x = vehicle.coord.x + motion.Speed*DELTA_T * cos(motion.Theta);
735         vehicle.coord.y = vehicle.coord.y + motion.Speed*DELTA_T * sin(motion.Theta);
736
737         /* ----------------------------------------------------------------------- *
738          * drive motors (former in motor.c)                                        *
739          * ----------------------------------------------------------------------- */
740
741         dd[0]=speed/wheelRadius[0]*16615.776;
742         dd[1]=speed/wheelRadius[1]*16615.776;
743         dd[2]=speed/wheelRadius[2]*16615.776;
744         dd[3]=speed/wheelRadius[3]*16615.776;
745
746
747         speedDigits[0]=(short)(0.0132421*dd[0]-1.15119);    /* set speed for wheel 1 */
748         speedDigits[1]=(short)(0.0132276*dd[1]-1.17617);    /* set speed for wheel 2 */
749         speedDigits[2]=(short)(0.0132283*dd[2]+0.17110);    /* set speed for wheel 3 */
750         speedDigits[3]=(short)(0.0132680*dd[2]+1.21652);    /* set speed for wheel 4 */
751
752         /* set the speeds */
753         setServoSpeed();
754
755     return;
756 } /* end of leoMotion() */
757
758 void linearMotion2(void)
759 {
760     double v1x, v1y, v2, v1yv1xRatio,omega2,omega3, beta,ro,ro2,wheelAngleV;
761     int ix,Speed_Digit,Steer_Digit;
762     short *servoOut;
763
764     /* read all shaft encoders */
765     readNewEncoder();
766
767     /* compute the actual rates, velocities and angles */
768     for (ix=0; ix<4; ix++){
769         driveSpeed[ix]=driveDelta[ix]*CM_PER_DIGIT/DELTA_T;    /* [cm/s] */
770         steerRate[ix]=steerDelta[ix]/DELTA_T;
771         steerAngle[ix]=steerAngle[ix]+steerDelta[ix]*RAD_PER_DIGIT;
772     } /* end of for ... */
773
774
775     /* initialize temporary variables */
776     speed=motion.Speed;
777     theta=motion.Theta;
778     omega=motion.Omega;
779
780     /* ----------------------------------------------------------------------- *
781      * body motion (former in movement.c)                                      *
782      * ----------------------------------------------------------------------- */
783
784     a=100.0;    /* max acceleration [cm/sec^2] */
785
786     /* no acceleration for t<1sec */
787
788     if ((time>=100)&&(time<200))
789         speed=0.005*(time-100)*(time-100); /* vehicle speed [cm/sec] (max is 50cm/sec */
790
791     if ((time>=300)&&(time<400))
792             speed=800.0+0.005*time*(time-800.0);
793
794     if (time==400){
795         mode=0;
796         stopVME9325();    /* stop A/D-Board */
797         allOffAndZero();
798     }
799
800     /* compute required derivatives */
801     speedDot=(speed-motion.Speed)/DELTA_T;
```

82

```
802      thetaDot=(theta-motion.Theta)/DELTA_T;
803      omegaDot=(omega-motion.Omega)/DELTA_T;
804
805      /* update the motion */
806      motion.Speed = speed;
807      motion.Theta = theta;
808      motion.Omega = omega;
809
810      /* update the vehicle configuration */
811      vehicle.heading = vehicle.heading + motion.Omega*DELTA_T;
812      vehicle.coord.x = vehicle.coord.x + motion.Speed*DELTA_T * cos(motion.Theta);
813      vehicle.coord.y = vehicle.coord.y + motion.Speed*DELTA_T * sin(motion.Theta);
814
815      /* ------------------------------------------------------------------- *
816       * drive motors (former in motor.c)                                    *
817       * ------------------------------------------------------------------- */
818
819      dd[0]=speed/wheelRadius[0]*16615.776;
820      dd[1]=speed/wheelRadius[1]*16615.776;
821      dd[2]=speed/wheelRadius[2]*16615.776;
822      dd[3]=speed/wheelRadius[3]*16615.776;
823
824
825      speedDigits[0]=(short)(0.0132421*dd[0]-1.15119);   /* set speed for wheel 1 */
826      speedDigits[1]=(short)(0.0132276*dd[1]-1.17617);   /* set speed for wheel 2 */
827      speedDigits[2]=(short)(0.0132283*dd[2]+0.17110);   /* set speed for wheel 3 */
828      speedDigits[3]=(short)(0.0132680*dd[2]+1.21652);   /* set speed for wheel 4 */
829
830      /* set the speeds */
831      setServoSpeed();
832
833   return;
834 } /* end of leoMotion2() */
835
836
837 /* --------------------------------------------------------------------------- *
838  * setServoSpeed()                                                             *
839  *                                                                             *
840  * Environment:  GCC Compiler v2.7.2                                           *
841  * Name:         Thorsten Leonardy                                             *
842  * Last update:  10/27/97                                                      *
843  * Purpose:      This function sets the speed as specified in global vars      *
844  *               speedDigits and steerDigits to all servo motors.             *
845  * Called from:  driver() in movement.c                                        *
846  * --------------------------------------------------------------------------- */
847 void setServoSpeed(void)
848 {
849
850   short *servoOut=(unsigned short*)(VME9210+0x0082);   /* Analog out     */
851
852   *servoOut++= -speedDigits[0]*16;       /* set speed for driving wheel 1 */
853   *servoOut++=  speedDigits[1]*16;       /* set speed for driving wheel 2 */
854   *servoOut++= -speedDigits[2]*16;       /* set speed for driving wheel 3 */
855   *servoOut++=  speedDigits[3]*16;       /* set speed for driving wheel 4 */
856
857   *servoOut++=  steerDigits[0]*16;       /* set speed for driving wheel 1 */
858   *servoOut++=  steerDigits[1]*16;       /* set speed for driving wheel 2 */
859   *servoOut++=  steerDigits[2]*16;       /* set speed for driving wheel 3 */
860   *servoOut++=  steerDigits[3]*16;       /* set speed for driving wheel 4 */
861
862   return;
863 } /* End of setServoSpeed */
864
865
866
867 /* --------------------------------------------------------------------------- *
868  * clearEncoder(motors)                                                        *
869  *                                                                             *
870  * Environment:  GCC Compiler v2.7.2                                           *
871  * Last update:  03 November 1997                                              *
872  * Name:         Thorsten Leonardy                                             *
873  * Purpose:      This function clears all shaft encoders.                      *
874  *                                                                             *
875  * motors        bit mask to select motors, eg. 0x042 selects motor 2 and 7   *
876  *               to be cleared.                                                *
877  * --------------------------------------------------------------------------- */
```

```
878   void clearEncoder(unsigned char motors)
879   {
880       unsigned char *p=(unsigned char*)VMECTR1;
881       int ix;
882
883       for (ix=0; ix<4; ix++,motors/=2) {
884           if (motors & 0x01) *(p+3)=0x04;        /* clear respective counter */
885           if (motors & 0x10) *(p+0x0103)=0x04;   /* clear steering counter   */
886           p=p+4;                                 /* access next pointer      */
887       }
888       return;
889   } /* end of clearEncoder */
890
891
892   /* -------------------------------------------------------------------- *
893    * align()                                                             *
894    * Environment:  GCC Compiler                                          *
895    * Last update:  07 August 1997                      m                 *
896    * Name:         Thorsten Leonardy and Yutaka Kanayama                 *
897    * Purpose:      This function will align SHEPHERD's wheels such that all  *
898    *               will point in the forward direction. It utilizes the hall *
899    *               sensors for each of the four wheels. All wheels are being *
900    *               aligned simultaneously rather than successively.      *
901    *                                                                     *
902    * -------------------------------------------------------------------- */
903   void align(void)
904   {
905       unsigned short *servoOut=(unsigned short*)(VME9210+0x008A);    /* Analog out */
906       unsigned short *servoStatus=(unsigned short *)(VME9421+0x00ca); /* digital input */
907       unsigned int   *servoControl=(unsigned int *)VME2170;          /* Data Out */
908       int ix;
909       unsigned short bitMask,speed=0x0200;
910
911       /* set steering speeds */
912       *servoOut=-speed;        /* wheel1 -> rotate CW */
913       *(servoOut+1)= speed;    /* wheel2 -> rotate CCW */
914       *(servoOut+2)= speed;    /* wheel3 -> rotate CCW */
915       *(servoOut+3)=-speed;    /* wheel4 -> rotate CW  */
916
917       bitMask=0xf000;
918
919       while(bitMask){
920         if ( 0x8000 & *servoStatus ){
921             *servoOut=0x0000;        /* set speed=0 for wheel 1 */
922             bitMask=bitMask & 0x7000;
923         }
924         if ( 0x4000 & *servoStatus ){
925             *(servoOut+1)=0x0000;    /* set speed=0 for wheel 2 */
926             bitMask=bitMask & 0xb000;
927         }
928         if ( 0x2000 & *servoStatus ){
929             *(servoOut+2)=0x0000;    /* set speed=0 for wheel 3 */
930             bitMask=bitMask & 0xd000;
931         }
932         if ( 0x1000 & *servoStatus ){
933             *(servoOut+3)=0x0000;    /* set speed=0 for wheel 4 */
934             bitMask=bitMask & 0xe000;
935         }
936       }
937
938       sioOut(0,"Aligned ...\n\r");
939
940       return;
941   } /* end of align */
942
943
944   /* ------------------------------------------------------- *
945    * all servos on and set zero speed, [added 11/05/97, Leo] *
946    * ------------------------------------------------------- */
947   void allOnAndZero(void){
948       unsigned int *servoControl=(unsigned int *)VME2170; /* Data Out */
949       short *servoOut=(unsigned short*)(VME9210+0x0082);   /* Analog out driving wheel1 */
950       int ix;
951
952       for (ix=0; ix<8; ix++) *servoOut++=0x0000;   /* set zero speed */
953
```

84

```
954      *servoControl=0x00924924;          /* turn on all motors */
955
956      return;
957 }  /* end of allOnAndZero */
958
959
960 /* ----------------------------------------------------------- *
961  * all servos off and set zero speed, [added 11/05/97, Leo] *
962  * ----------------------------------------------------------- */
963 void allOffAndZero(void){
964     unsigned int *servoControl=(unsigned int *)VME2170; /* Data Out */
965     short *servoOut=(unsigned short*)(VME9210+0x0082);   /* Analog out driving wheel1 */
966     int ix;
967
968     for (ix=0; ix<8; ix++) *servoOut++=0x0000;   /* set zero speed */
969
970      *servoControl=0x00000000;          /* turn on all motors */
971
972     return;
973 }  /* end of allOffAndZero */
974
975
976 /* --------------------------------------- *
977  * Set all driving motors to specific speed *
978  * --------------------------------------- */
979 void allDrive(short digit){
980     unsigned int *servoControl=(unsigned int *)VME2170; /* Data Out */
981     short *servoOut=(unsigned short*)(VME9210+0x0082);   /* Analog out driving wheel1 */
982     int ix;
983
984     for (ix=0; ix<4; ix++) *servoOut++=digit;    /* set zero speed */
985
986     *servoControl=0x00000924;           /* turn on driving motors */
987
988     return;
989 }  /* end of allDrive */
990
991
992 /* --------------------------------------- *
993  * Set all steering motors to specific speed *
994  * --------------------------------------- */
995 void allSteer(short digit)
996 {
997     unsigned int *servoControl=(unsigned int *)VME2170; /* Data Out */
998     short *servoOut=(unsigned short*)(VME9210+0x008A);   /* Analog out steering wheel1 */
999     int ix;
1000
1001     for (ix=0; ix<4; ix++) *servoOut++=digit;    /* set zero speed */
1002
1003     *servoControl=0x00924000;            /* turn on steering motors */
1004
1005     return;
1006 }  /* end of allSteer */
1007
1008
1009 /* --------------------------------------------- *
1010  * switches all motors off [added 11/05/97, Leo] *
1011  * --------------------------------------------- */
1012 void allMotorsOff(void){
1013     unsigned int *servoControl=(unsigned int *)VME2170; /* Data Out */
1014
1015      *servoControl=0x00000000;          /* turn off all motors */
1016
1017     return;
1018 }  /* end of allMotorsOff */
1019
1020
1021 /* --------------------------------------------- *
1022  * switches all motors on [added 11/05/97, Leo] *
1023  * --------------------------------------------- */
1024 void allMotorsOn(void){
1025     unsigned int *servoControl=(unsigned int *)VME2170; /* Data Out */
1026
1027      *servoControl=0x00924924;          /* turn on all motors */
1028
1029     return;
```

```
1030  }  /* end of allMotorsOn */
1031
1032
1033  /* ------------------------------------------------------------------------- *
1034   * driveTest()                                                                *
1035   *  *                                                                          *
1036   * Environment:  GCC Compiler v2.7.2                                          *
1037   * Last update:  29 October 1997                                             *
1038   * Name:         Thorsten Leonardy                                           *
1039   * Purpose:      This function computes the actual servo data for all        *
1040   *               driving motors.                                             *
1041   * Called from:  user() upon keyboard interaction (type 'd')                 *
1042   * ------------------------------------------------------------------------- */
1043  void driveTest()
1044  {
1045     unsigned int    *servoControl=(unsigned int *)VME2170;          /* Data Out */
1046     unsigned short *servoOut=(unsigned short*)(VME9210+0x008A);      /* Analog out */
1047     unsigned short *ser  Status=(unsigned short *)(VME9421+0x00ca); /* digital input */
1048     unsigned short bitk   =0x8000;         /* access bit 15 for align  wheel 1 */
1049     unsigned char *p;
1050     unsigned int wheelSelect;
1051     int ix;
1052
1053     *servoControl=0x00000000;              /* disable (turn off) all wheels    */
1054
1055     servoOut=(unsigned short*)(VME9210+0x0082);   /* Analog out for drive wheel 1*/
1056     wheelSelect=0x00000004;                        /* select servo for driving wheel 1 */
1057
1058     p=(unsigned char*)VMECTR1;
1059
1060     for (ix=0; ix<4; ix++) {
1061
1062        *servoOut=testSpeed;               /* set output value for servo first      */
1063        *servoControl=wheelSelect;         /* turn on selected servo motor          */
1064
1065        sioOut(0,"Press '.' to start recording time\n\r");
1066
1067        while (key!='.') ;                 /* wait until user starts */
1068
1069        *(p+3)=0x04;                        /* clear counter for driving wheel ix */
1070
1071        readOneEncoder(ix,(int *)&driveCountPrevious[ix]); /* update encoder */
1072        readOneEncoder(ix,(int *)&steerCountPrevious[ix]); /* update encoder */
1073
1074        timeForTurn[ix]=intCounter;     /* store time (start observing) */
1075
1076        sioOut(0,"Press ',' to stop recording time\n\r");
1077
1078        while (key!=',') ;                 /* wait until user stops the process */
1079
1080        timeForTurn[ix]=intCounter-timeForTurn[ix];
1081
1082        *servoOut++=0x0000;                /* stop wheel */
1083
1084        readOneEncoder(ix,(int *)&driveCount[ix]); /* update encoder */
1085        readOneEncoder(ix,(int *)&steerCount[ix]); /* update encoder */
1086
1087        driveDelta[ix]=(driveCount[ix]-driveCountPrevious[ix])/256;
1088        steerDelta[ix]=(steerCount[ix]-steerCountPrevious[ix])/256;
1089
1090        wheelSelect= wheelSelect<<3;     /* select next servo (motor)        */
1091
1092     }
1093
1094     *servoControl=0x00000000;              /* disable (turn off) all wheels    */
1095
1096     return;
1097  } /* end of driveTest */
1098
1099
1100  /* ------------------------------------------------------------------------- *
1101   * velocityTest()                                                             *
1102   *  *                                                                          *
1103   * Environment:  GCC Compiler v2.7.2                                          *
1104   * Last update:  07 November 1997                                            *
1105   * Name:         Thorsten Leonardy                                           *
```

```
1106   * Purpose:        This function obtaines the velocity versus digit curve.    *
1107   *                 Drive servos are given different velociies (digit) every    *
1108   *                 two seconds. The first second is to obtain steady state, the*
1109   *                 second second will record the shaft encoder difference, thus*
1110   *                 giving rise to a encoder reading versus velocity curve.      *
1111   *                 The commanded velocity goes from 500 .. -510 at present.     *
1112   *                                                                              *
1113   * Called from:  user() upon keyboard interaction (type 'v')                    *
1114   * ------------------------------------------------------------------------- */
1115   void velocityTest(void)
1116   {
1117       unsigned int *servoControl=(unsigned int *)VME2170; /* Data Out */
1118       short *servoOut=(unsigned short*)(VME9210+0x0082);   /* Analog out driving wheel1 */
1119       ..
1120       short speed,digit;
1121
1122       speed=500;
1123       digit=speed*16;
1124
1125       leoData=(int *)0x00100000;     /* start data storage */
1126
1127       sioOut(0,"velocityTest\n\r");
1128       align();
1129       allOffAndZero();
1130
1131       *servoControl=0x00000924;            /* turn on driving motors */
1132
1133       readNewEncoder();
1134       time=0;                    /* this will be altered by timer interrupt */
1135
1136       /* set new driving values */
1137       *servoOut++=-digit;    /* set speed for wheel 1 */
1138       *servoOut++= digit;    /* set speed for wheel 2 */
1139       *servoOut++=-digit;    /* set speed for wheel 3 */
1140       *servoOut++= digit;    /* set speed for wheel 4 */
1141
1142       while (speed>-510) {
1143
1144           servoOut=(short *)(VME9210+0x0082);
1145
1146           /* set new driving values */
1147           *servoOut++=-digit;    /* set speed for wheel 1 */
1148           *servoOut++= digit;    /* set speed for wheel 2 */
1149           *servoOut++=-digit;    /* set speed for wheel 3 */
1150           *servoOut++= digit;    /* set speed for wheel 4 */
1151
1152           speed=speed-10;
1153           digit=speed*16;   /* shift nibble left */
1154           time=0;
1155
1156           /* wait a second for motors to settle */
1157           while(time<100) ;
1158
1159           readNewEncoder();
1160
1161           /* record for a second */
1162           while(time<200) ;
1163
1164           readNewEncoder();
1165
1166
1167           /* store the counter data for previous speed */
1168           *leoData++=steerDelta[0];
1169           *leoData++=steerDelta[1];
1170           *leoData++=steerDelta[2];
1171           *leoData++=steerDelta[3];
1172           *leoData++=driveDelta[0];
1173           *leoData++=driveDelta[1];
1174           *leoData++=driveDelta[2];
1175           *leoData++=driveDelta[3];
1176       }
1177
1178       allOffAndZero();
1179
1180       return;
1181   } /* end of velocityTest */
```

87

```
1182
1183
1184   /* -------------------------------------------------------------------- *
1185    * circumferenceTest()                                                  *
1186    *                                                                      *
1187    * Environment:   GCC Compiler v2.7.2                                   *
1188    * Last update:   07 November 1997                                      *
1189    * Name:          Thorsten Leonardy                                     *
1190    * Purpose:       This function drives the vehicle in a straight line and *
1191    *                stores the difference for all shaft encoders for a given *
1192    *                observation time. If the distance travelled is being  *
1193    *                measured, one can obtain the relation between shaft encoder *
1194    *                readings and wheel diameter.                          *
1195    * Called from:   user() upon keyboard interaction (type 'c')           *
1196    * -------------------------------------------------------------------- */
1197   void circumferenceTest(void)
1198   {
1199       unsigned int *servoControl=(unsigned int *)VME2170; /* Data Out */
1200       short *servoOut=(unsigned short*)(VME9210+0x0082);   /* Analog out driving wheel1 */
1201
1202       short speed,digit;
1203
1204       speed=300;
1205       digit=speed*16;
1206
1207       leoData=(int *)0x00100000;     /* start data storage */
1208
1209       sioOut(0,"circumferenceTest()\n\r");
1210
1211       align();
1212       allOffAndZero();
1213
1214       *servoControl=0x00000924;          /* turn on driving motors */
1215
1216       /* determine the digits to command based on linea4r relationship obtained *
1217        * in velocityTest for each wheel individually.                          */
1218
1219       /* assume for one second, that driveDelta=10000 */
1220
1221
1222       /* set new driving values for driveDelta approx 10000 over 1 sec */
1223       *servoOut++=(short)(-16*(0.0132421*ddc-1.15119));   /* set speed for wheel 1 */
1224       *servoOut++=(short)( 16*(0.0132276*ddc-1.17617));   /* set speed for wheel 2 */
1225       *servoOut++=(short)(-16*(0.0132283*ddc+0.17110));   /* set speed for wheel 3 */
1226       *servoOut++=(short)( 16*(0.0132680*ddc+1.21652));   /* set speed for wheel 4 */
1227
1228       time=0;                    /* this will be altered by timer interrupt */
1229       readNewEncoder();
1230
1231       while (time<tc) ;      /* wait 2 sec */
1232
1233       readNewEncoder();
1234
1235       allOffAndZero();
1236
1237       return;
1238   } /* end of circumferenceTest */
1239
1240
1241
1242   /* -------------------------------------------------------------------- *
1243    * steerTest()                                                          *
1244    *                                                                      *
1245    * Environment:   GCC Compiler v2.7.2                                   *
1246    * Last update:   29 October 1997                                       *
1247    * Name:          Thorsten Leonardy                                     *
1248    * Purpose:       This function computes the actual servo readings for all *
1249    *                steering motors.                                      *
1250    * Called from:   user() upon keyboard interaction (type 'w')           *
1251    * -------------------------------------------------------------------- */
1252   void steerTest()
1253   {
1254       unsigned int    *servoControl=(unsigned int *)VME2170;              /* Data Out */
1255       unsigned short *servoOut=(unsigned short*)(VME9210+0x008A);      /* Analog out */
1256       unsigned short *servoStatus=(unsigned short *)(VME9421+0x00ca); /* digital input */
1257       unsigned char *p;
```

```
1258     unsigned short bitMask=0x8000;        /* access bit 15 for align  wheel 1 */
1259     unsigned int wheelSelect=0x00004000; /* select servo for turning wheel 1 */
1260     int ix,turns,a;
1261
1262     /* align wheels */
1263     align();
1264
1265     /* clear all driving and steering motor counters and the variables */
1266     clearEncoder(0xff);
1267
1268     servoOut=(unsigned short*)(VME9210+0x008A); /* Analog out for steering wheel 1  */
1269     bitMask=0x8000;                            /* access bit 15 for align  wheel 1 */
1270     wheelSelect=0x00004000;                    /* select servo for turning wheel 1 */
1271
1272     readNewEncoder();                          /* read all encoders */
1273
1274     for (ix=0; ix<4; ix++) {
1275
1276        turns=0;
1277        *servoOut=testSpeed;              /* set output value for servo first      */
1278        *servoControl=wheelSelect;   /* turn on selected servo motor          */
1279
1280        /* turn wheels for a total of 10 turns */
1281        do {
1282           while(!(bitMask&*servoStatus));  /* wait until wheel aligned    */
1283           while(bitMask&*servoStatus);     /* wait until wheel progressed */
1284           turns++;                         /* one turn completed          */
1285           if (turns==1)
1286              timeForTurn[ix]=intCounter;    /* store time (start observing) */
1287           if (turns==9){
1288              timeForTurn[ix]=(intCounter-timeForTurn[ix])/8;   /* stop timer */
1289              *servoOut++=0x0800;              /* speed for final turn  */
1290           }
1291        }while (turns<10);
1292
1293        wheelSelect= wheelSelect<<3;      /* select next servo (motor)        */
1294        bitMask = bitMask >> 1;           /* select ner xt status align bit   */
1295     }
1296
1297     *servoControl=0x00000000;             /* disable (turn off) all wheels    */
1298
1299     readNewEncoder();
1300
1301     for (ix=0; ix<4; ix++) radPerDigit[ix]=2.0*PI*10.0/(double)steerDelta[ix];
1302
1303     return;
1304 } /* end of steerTest */
1305
1306
1307 /* ------------------------------------------------------------------------- *
1308  * stopTest()                                                               *
1309  *                                                                          *
1310  * Environment:  GCC Compiler v2.7.2                                        *
1311  * Last update:  03 November 1997                                           *
1312  * Name:         Thorsten Leonardy                                          *
1313  * Purpose:      This function computes the actual servo readings for all   *
1314  *               steering motors while the motor speeds are set to zero.    *
1315  * Called from:  user() upon keyboard interaction (type 's')                *
1316  * ------------------------------------------------------------------------- */
1317 void stopTest()
1318 {
1319
1320     sioOut(0,"Aligning Wheels ...\n\r");
1321
1322     align();    /* align wheels */
1323
1324     /* clear all driving and steering motor counters and the variables */
1325     clearEncoder(0xff);
1326
1327     readNewEncoder();
1328     allOnAndZero();
1329
1330     time=0;
1331     sioOut(0,"Please Wait a minute ...\n\r");
1332     while (time<6000) ;   /* wait a minute */
1333     allOffAndZero();
```

```
1334
1335        sioOut(0,"Done\n\r");
1336        readNewEncoder();
1337
1338        return;
1339   } /* end of stopTest */
1340
1341
1342
1343
1344   /********************************************************************
1345      End of motor.c
1346      ********************************************************************/
```

APPENDIX D: SHEPHERD PRIMER

This appendix provides essential data and procedures which lead to the findings of the motion parameters that are required to operate SHEPHERD properly. Boxed text will refer to a segment of software code or a command sequence for use in the TAURUS Debugger environment. The focus is on the use of the TUARUS Debugger since this provides a quick way to determine most of the operating parameters.

1.   MAIN OPERATING PARAMETERS AND CONVERSION FACTORS

It is sometimes tedious to gather the meat for operating a system. This section strives to provide most of the operating parameters pertaining to the use of SHEPHERD in tabulated form.

Wheel Radius	0.189 m
max. Tire pressure	49.8 psi
Drive Encoder (all Wheels)	2π radians = 360 * 290 counts
	1 m = 87914 counts
	1 count = 11.37 μm
Wheel 1	digit = 187.20 v [cm/sec] - 26.4
Wheel 2	digit = 187.04 v [cm/sec] - 26.4
Wheel 3	digit = 186.88 v [cm/sec] - 4.8
Wheel 4	digit = 187.20 v [cm/sec] + 8.8
Steer Encoder (all Wheels)	2π radians $\equiv$ 360 * 256 counts
	1 degree = 256 counts

Table 4.1: Shepherd Operating Parameters in a Nutshell

2.   RESET AND READ SHAFT ENCODERS

To find out how the servo readings relate to either the steering and/or the driving, use the following debugger sequence which resets the servo counter for one wheel, drives the wheel and reads the servo counter after steering is done. The same procedures would apply for use with the remaining servo motors.

```
Taurus_Bug>ms ffff610b 04        & clear servo counter for steering wheel 3
Taurus_Bug>ms ffff048e 0800      & set velocity for steering wheel 3
Taurus_Bug>ms ffffff00 00100000  & turn on motor for steering wheel 3
                                 & ... after a certain number of revolutions ...
Taurus_Bug>ms ffffff00 00000000  & turn off motor for steering wheel 3
Taurus_Bug>ms ffff610b 03        & select control for motor 7 (steer wheel 3)
Taurus_Bug>ms ffff610b 01        &
Taurus_Bug>md ffff6109:1;b       & read least significant byte of 24bit counter
FFFF6109 D3                      & the result
Taurus_Bug>md ffff6109:1;b       & read next byte ...
FFFF6109 C6                      & ... the result
Taurus_Bug>md ffff6109:1;b       & read most significant byte ..
FFFF6109 FB                      & ... the result
Taurus_Bug>                      & the complete counter value in this case is
                                 & 0xfbc6d3 sign-extended (e.g. -276781)
```

3.   UP- AND DOWNLOADING DATA FROM TAURUS BOARD

At this time, there is no straight forward routine for data up- and downloading available. Hence, the up- and downloading of data such as waypoints, ... is very tedious. The only way, data can be transferred from or to the TAURUS main memory is via the TAURUSBug options 'du' for downloading data to the Laptop and 'lo'. However, data would be made available only in form of the Motorola S-Record format.

To download data from the TAURSU main memory to the Laptop, the Laptop must capture the script sent to the screen to a file (option "T"ext "C"apture on the menu bar). In a second step, output the data to the screen using the folowing command:

```
Taurus_Bug>du0 100000 1000ff 'This is a dump to the screen'
Effective address: 00100000
Effective address: 001000ff
S01F00005468697320697320612064756D7020746F20746865207363726566656EF1
S214100000012341234123412341234123412341234AB
S214100010012341234123412341234123412341234349B
S214100020012341234123412341234123412341234368B
S214100030012341234123412341234123412341234347B
S214100040012341234123412341234123412341234346B
S214100050012341234123412341234123412341234345B
S214100060012341234123412341234123412341234344B
S214100070012341234123412341234123412341234343B
S214100080012341234123412341234123412341234342B
S214100090012341234123412341234123412341234341B
S2141000A0012341234123412341234123412341234340B
S2141000B0012341234123412341234123412341234FB
S2141000C0012341234123412341234123412341234EB
S2141000D0012341234123412341234123412341234DB
S2141000E0012341234123412341234123412341234CB
S2141000F0012341234123412341234123412341234BB
S9030000FC
Taurus_Bug>
```

As can be seen above, the data from memory location 0x100000 to 0x1000ff will be output to the screen and thus captured in the ascii file specified. However, the data will be in the Motorola S-Record format and a parsing program needs to extract the pure data. The parsing program however, needs to know the datatype of the data given to extract the correct information. E.g., extracting data of datatype 'integer' would require a different parsing routine.

As far as the uploading of data is concerned, the datafile must be transferred in the same manner as the SRK program, with the 'LO' option and described by [1].

4.   INTERRUPTS

This section describes briefly what type of interrupts are enabled on SHEPHERD.

a.   Timer Interrupt

Every 10 ms, a timer interrupt is issued by the on board timing circuit. The interrupt handling routine 'TimerHandler' does the following:

1. increments counter 'intCounter'
   (which may be needed for timing purposes)

2. initiate (software trigger) a block conversion for the A/D-Board AVME9325-5

3. call function 'driver' in file 'movement.c' to execute/handle motion control part

The interrupt is routed through the Interrupt steering mechanism (ISM) to the VIC068 and from there to the 68040 processor in the following way:
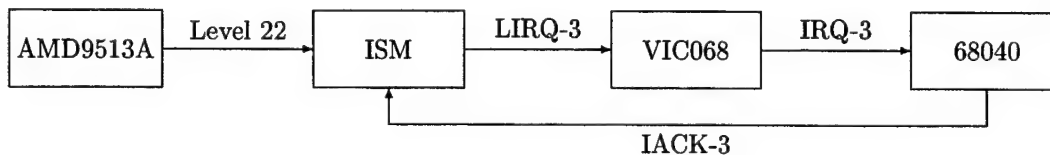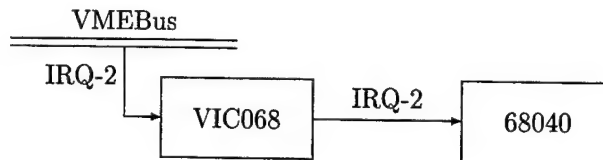

b.   A/D-Board Interrupt

Every 10 ms, the timer circuit initiates the start of a block conversion on the A/D-Board. Once this conversion is complete, the A/D-Board AVME9325-5 issues an interrupt to indicate that

the conversion is complete and data is available to be read from its dual port RAM. The interrupt handler **'handlerVME9325()'** then subsequently calls 'analyzeData' to further analyze/process the data. The interrupt vector number is provided by the Board and set to be 0x0056 which relates to the location of the address for interrupt handling routine at 0x0158 in the interrupt vector table.

As opposed to on-board interrupts, the interrupt from the A/D-Converter VME board is routed directly through the VIC068 to the 68040 processor:

c. **Keyboard Interrupt**

The overarching framework for user interaction is provided by the routine 'user()' in file 'user.c'. Each time, the keyboard is pressed, an interrupt is issued by the 68C681 on board serial circuit to the 68040 through the ISM and VIC068. The ascii code for the key pressed is then be stored in the variable inPortA and further analyzed by the routine 'user()' in file 'user.c'. The mode flags set in this function will be further processed by functions called during the motion control cycle following each 10ms timer interval. For this interrupt, the interrupt vector number is provided by the DUART and set to be 0x0060 thus giving rise to the location of the interrupt handling routine **inPortAHandler** at 0x0180 in the interrupt vector table.
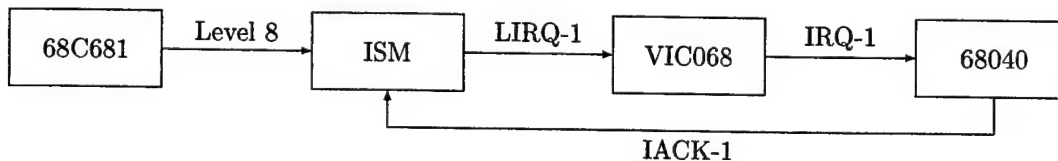
5. REPRESENTATION OF DOUBLE VARIABLES

According to the M68040 users manual, any double-precision variable is stored in memory as an 8 byte data value in the following form

Since the representation is normalized with the leading (implicit) bit always one we find the relation

Bit 63 = s = sign bit (1=negative number)	
Bit 62..52 = e = 11 bit exponent in the range 0x000 ... 0x7ff	
Bit 51..0 = f = 52 bit (13 nibbles) binary decimal (mantissa)	
in the range 0x0000000000000 ... 0xfffffffffffff	

to the real number representation x by

$$x = (-1)^s\ 2^{e-0x3ff}\ (1+d)$$

with $d = f \cdot 2^{-52}$. As an example, to display the double variable stored in memory location 0x306e8 we issue the following TAURUSbug commands

```
Taurus_Bug>md 306e8:1;d
000306E8 1_3F1_1DF44179E4364
```

The result is conveniently displayed by the monitor such that the elements can be easily identified: s=1, e=0x03f1, f=0x1df44179e4364. Hence, the real number is

$$x = (-1)^1\ 2^{(0x03f1-0x03ff)}\ (1 + \frac{0x01df44179e4364}{0x10000000000000})$$

6.   HOW TO RUN SHEPHERD'S WHEELS

Three VME boards account for operating of the wheels, both in steering and driving. These boards are accessible via the VME Bus Port connector P1 and they are:

Board	Function	GCC Access
VME 9210	Analog Output to servos (velocity)	short
VME 2170	Servo Control (on/off)	unsigned int
VME 9421	Servo Status	unsigned short

Shepherd is equipped with a total of eight servo motors: four wheels with driving and turning capability. The setup and software configuration is depicted in Figure (1). In order to operate each one of the motors one has to perform the following steps:

1. Select the angular velocity for the motor by writing a signed short value (16 Bit) to the respective channel (see Figure 1 for the channel assignments) on the VME9210 board (analog Output). E.g. to turn wheel 3 (rear right) one would write

```
*(ffff048e)=(short)velocity;
```

where a positive velocity corresponds to the spin direction as indicated by the arrow in Fig. (1). The well known Right-Hand rule applies for determining the direction of spin.

2. Switch the motor on/off by writing the respective mask to VME2170 at 0xffffff00. Refer to Fig. (1) for the mask assignment. E.g. to drive wheel 2 (front left) and turn wheel 4 (rear left) simultaneously, one would issue the command

```
*(0xffffff00)=(unsigned int)0x00800020
```

Any combination is allowed, i.e. mask 0x00900000 would turn wheels 3 and 4. Make sure you have set the angular velocities for the wheels you are going to run as outlined in step 1 above!

A word of Caution: for driving wheels 1 (front right) and 3 (rear right) forward, negative values must be written to the VME9210 Board as outlined in step 1.
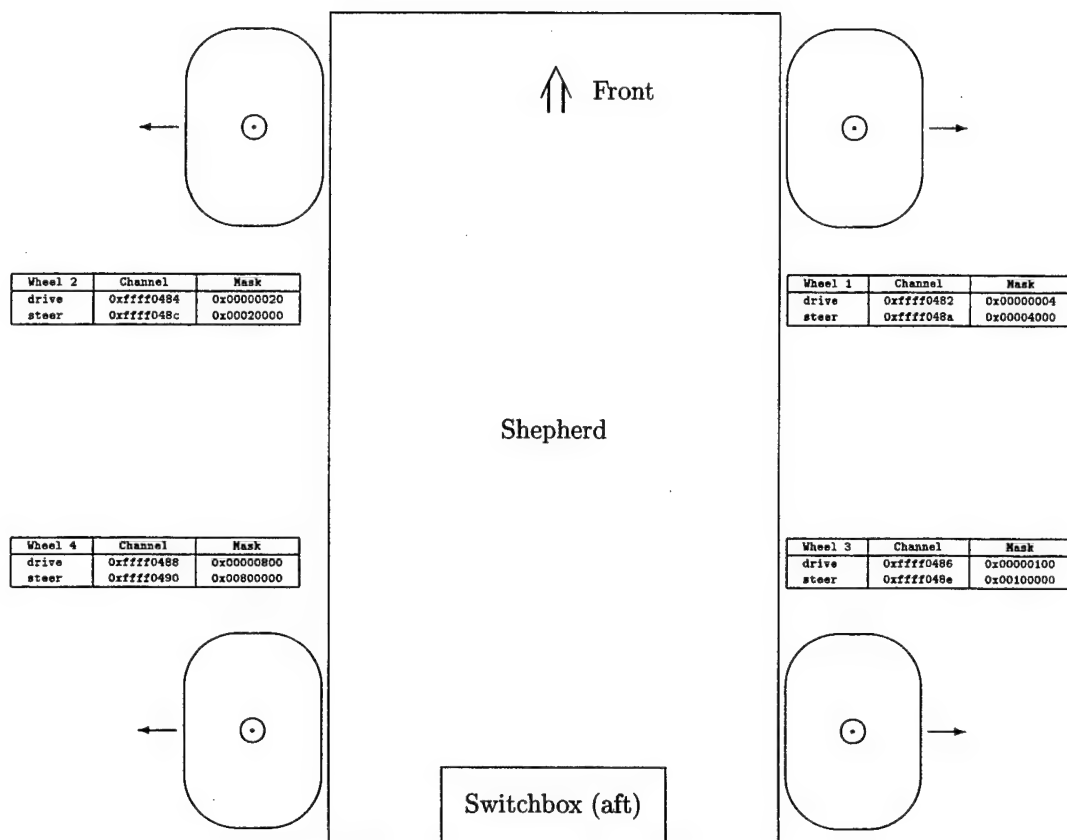

Figure 4.1: Wheel Assignment and Servo Register Addressing (Arrows and Dots at each wheel indicate the rotation of the respective servos if controlled with positive values.

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